Exhibit 27

Technical Assessment of Ignition Switch Test Methods, Procedures and Analysis Techniques

Final Report Delivered to General Motors by the Virginia Tech Transportation Institute

August 30, 2014

By: *Thomas A. Dingus, Luke Neurauter, Kevin Kefauver, and Mindy Buchanan-King*

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This work was sponsored by General Motors and was conducted by the Virginia Tech Transportation Institute.

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EXECUTIVE SUMMARY

During July 2014, General Motors (GM) contracted the Virginia Tech Transportation Institute (VTTI) to perform a thorough, independent evaluation of the company's ignition switch testing. This testing was implemented following GM's ignition switch recall, the first of which was issued during February 2014 (GM, 2014b). GM is currently using three ignition switch tests to assess how internal and external forces may act upon the vehicle and/or ignition key to cause an inadvertent change in the ignition status from "Run" to "Accessory" or "Off." These three tests are: 1) Inertial, 2) Knee key, and 3) Hang tag.

The GM inertial test involves objectively measuring vehicle dynamics, such as acceleration, that could cause an inadvertent change in the ignition switch position. For this test, GM engineers equip vehicle samples with an accelerometer and an ignition key configuration that includes key weights up to 0.7 lb. The sample vehicles are run across eight events at the Milford Proving Grounds (MPG). These events are designed to exceed conditions found during "normal" driving and instead replicate the higher end of dynamic conditions that may be experienced by vehicles during more abnormal driving events (e.g., off-road).

The knee-key test involves both subjective and objective measures to determine the likelihood of a driver contacting the ignition key with his/her knee and creating enough force to turn the ignition key out of the "Run" position. During this test, GM staff representing what the company has classified as the 5th percentile female, 50th percentile male, and 99th percentile male are asked to sit inside a sample vehicle and adjust the seat and steering column to their individual, normal driving positions. Each percentile representative then rates how easy it is to rotate the ignition key with his or her knee (on a scale of easy, medium, difficult) and determine what driving position he or she would need to be in to achieve knee contact with the ignition key (rated as abnormal or normal driving). Measurements are then taken in a straight line from the driver's knee to the ignition key and any key fob to determine spatial relationships between the ignition switch and the driver's knee.

The hang tag test is both objective and subjective in nature and involves GM staff manipulating a hang tag in such a way as to determine if it can become caught within

the steering column and/or wheel to produce enough torque to move the ignition key out of the "Run" position.

To evaluate the robustness and validity of GM's three ignition switch tests, VTTI performed a series of comparative analyses using data primarily available from GM and the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS; Dingus et al., 2014) database housed at VTTI. The SHRP 2 NDS, the largest study of its kind ever undertaken, was conducted by VTTI and other contractors for the National Academy of Sciences during a three-year period and comprises more than 35 million miles of continuous naturalistic data collected from more than 3,000 voluntary participants. At 2 petabytes of data, the study captures such vehicle parameters as acceleration and ignition state, with video data available for each participant from key-on to key-off.

During its evaluation of the GM ignition switch tests, VTTI determined the following:

1. Inertial tests conducted at the GM MPG are robust and valid in determining scenarios during which inertial effects could rotate the ignition switch out of the "Run" position.
   - These tests will uncover the majority of inertial-based issues.
   - The tests appear to have a relatively low miss/false alarm rate (i.e., GM is finding what needs to be found during its inertial testing).

2. MPG testing could be reduced or even potentially eliminated if a large enough database of static models is created to robustly determine inertial effects.

3. The GM knee-key test, although somewhat subjective, is acceptable for examining this risk within existing vehicles.
   - However, enhancements are recommended to standardize the knee-key test process and quantify/improve results for future testing.
   - The potential exists to incorporate knee-key criteria into the current ergonomic design model at GM, further reducing future vehicle design issues relative to ignition switches.

4. The GM hang tag test is robust to the point of creating false alarms.
   - Hang tag is a rare event that is highly variable.
   - Hang tag events often occur at lower speeds, making a hang tag event generally less risky compared to inertial or knee-key events.
   - However, lessons learned from hang tag testing to date can and should be considered in future designs of GM vehicles.

5. The GM hang tag test should be eliminated as a separate test and combined with knee-key testing/modeling.
   - VTTI believes that a significant portion of hang tag issues involve knee contact.
   - Pure kinematic hang tag cases are probably very rare and may involve many keys/items hanging from the ignition key.

6. A primary issue in all three ignition switch scenarios is what drivers choose to hang from the ignition key (e.g., lanyards, other keys, fobs, etc.).
   - Although the majority of unintended changes in the ignition switch position can be eliminated through testing and design, educating and persuading drivers to adhere to reasonable guidelines remains an important control strategy.
   - A variety of countermeasures are suggested for consideration.
   - This is an industry-wide issue.

In summary, VTTI found through its independent analyses that, overall, GM engineers have made significant progress in creating a robust series of tests that have performed well and will continue to perform as constructed. That is, GM is using a series of tests that will determine the likelihood of ignition switch issues, thus allowing for countermeasures to be developed for current vehicles, with the ultimate goal of implementing and enhancing these tests in future vehicle models to design out any ignition switch issues before they occur.

As a result, VTTI believes the majority of existing ignition switch cases have been identified by GM, and the company's control strategies should result in a substantial reduction of unintended ignition deactivation cases.

Detailed recommendations for further refinement of GM's testing procedures and control strategies are contained within this report, as are recommended test enhancements for future vehicle designs.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	anti-lock braking system
ANSUR	Anthropometric Survey
CAESAR	Civilian American and European Surface Anthropometry Resource Project
CAMP	Crash Avoidance Metrics Partnership
CAN	controller area network
DAS	data acquisition system
FMCSA	Federal Motor Carrier Safety Administration
GM	General Motors
MPG	Milford Proving Grounds
Ncm	Newton centimeters
NHTSA	National Highway Traffic Safety Administration
OEM	original equipment manufacturer
SHRP 2 NDS	Second Strategic Highway Research Program Naturalistic Driving Study
SUFS	Speak Up for Safety
VTTI	Virginia Tech Transportation Institute

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INTRODUCTION

This is a final report resulting from the General Motors (GM) and Virginia Tech Transportation Institute (VTTI) contract "Technical Assessment of Ignition Switch Test Methods, Procedures and Analysis Techniques." As will be reiterated throughout the report, the goal of this project was for VTTI to provide an independent evaluation of the ignition switch tests conducted by GM and to determine the validity and robustness of such tests. VTTI was also asked to recommend enhancements to the GM tests, if such enhancements were deemed necessary during the course of the project work.

Because of the high-profile nature of the GM ignition switch recall, limited information will be provided herein about the background and current state of the GM recall process. Such information is available publicly; to reiterate it would be unnecessary towards the goal of this project. This report, instead, is intended to evaluate via a technical assessment what GM is doing now, and what it can do in the future, to test its ignition switches and ensure that such switches operate without defects. It is not the intent of VTTI, nor is it the goal of this project, to assess how GM handled the recall, make any presumptions regarding litigation surrounding ignition switch issues, hypothesize about the culpability of GM, etc.

The final report of this project is intended to: 1) Provide GM with an assessment of its ignition switch tests and recommendations as required by contract with VTTI, 2) Provide stakeholders and safety organizations with a potential guideline for an industry-wide assessment of ignition switch defects, and 3) Provide the public with an understanding of what GM is doing to test for ignition switch defects.

The report is structured as follows:

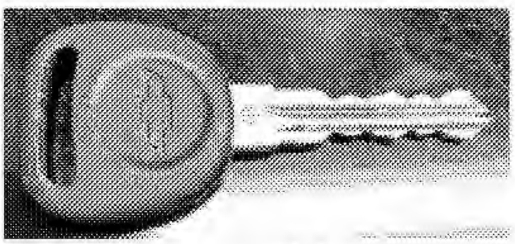
1. Introductory materials of the problem that led to the need for GM to create ignition switch tests, how the current GM tests were created and how they are conducted, why VTTI became involved as an independent evaluator, and how VTTI approached a technical assessment of the GM ignition switch tests;
2. The technical analysis of the GM inertial test;
3. The technical analysis of the GM knee-key test;
4. The technical analysis of the GM hang tag test;

5. Suggested countermeasures and design considerations that may be implemented to further help mitigate, and eventually eliminate, ignition switch defects; and
6. Conclusions and recommended follow-on work that may enhance GM's ignition switch tests and processes.

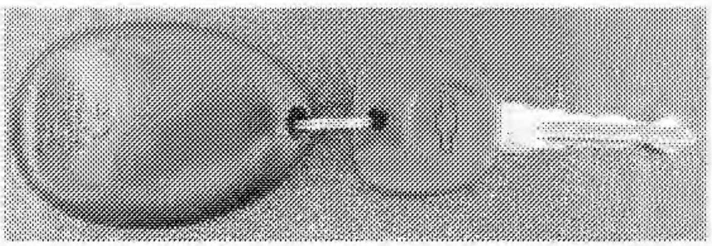
GM Ignition Switch Recall and Repair

In 2014, GM recalled more than 2.5 million vehicles for ignition switch issues. Per GM, these vehicles were recalled because of a "risk, under certain conditions, that your ignition switch may move out of the 'run' position, resulting in a partial loss of electrical power and turning off the engine" (GM, 2014a). The risk of encountering such an event increased if the key ring attached to the ignition key "carried added weight (such as more keys or the key fob) or if your vehicle experiences rough road conditions or other jarring or impact related [sic] events" (GM, 2014a). To avoid unintended consequences, most airbags are designed not to deploy within several seconds of loss of power to the vehicle. Thus, an inadvertent move in the ignition switch out of the "Run" position may result in a non-deployment of airbags during a crash, thereby increasing the risk of injury or fatality.

In light of the ignition switch recall issued by GM, the company created several countermeasures to combat an unintentional change in the ignition switch position. Owners of affected GM vehicles are being asked to use only one key to turn on the ignition (e.g., no key fob attachment, key chains, other keys, etc.) until they take their vehicles to a dealership for repair under the recall. GM vehicle owners whose vehicles are repaired under the recall are being issued either a new key with a hole design in the key head or a key with an insert that transitions the key head design from a slot to a hole (Figure 1 and Figure 2). The repair also includes a lock cylinder replacement to mitigate an unintentional ignition key pullout when not in the "Off" position, though VTTI was not asked to assess this issue.



(a)



(b)

Figure 1. Pre-recall slot key head design (a); post-recall Cobalt key with hole design in key head (b). Photos courtesy of GM.

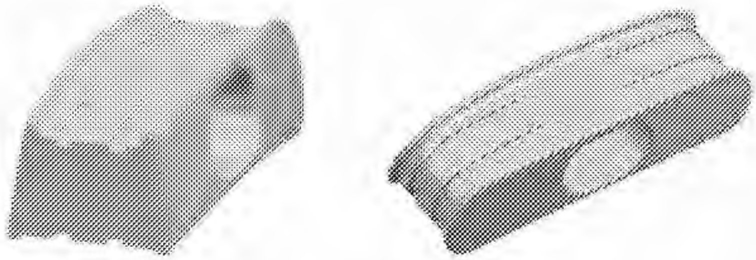


Figure 2. Insert with hole design (photo courtesy of GM).

The two countermeasures designed for the ignition switch repair essentially address factors that could influence the force and motion, or the inertial effects, placed on the ignition key configuration (e.g., key chains, hang tags, fobs, other keys, etc.) and unintentional knee contact. Both inertial and knee-key effects could result in an accidental move in the ignition switch out of the "Run" position. By limiting the ignition key to a single key until an owner has his/her affected vehicle repaired, GM has removed two main inertial forces (mass and length, both created by items attached to the ignition key) that could interact with an ignition switch to cause an unintentional change in the ignition switch position. The request to use only a single key until the vehicle has undergone the ignition switch repair also ensures that inadvertent knee contact is mitigated. That is, removing all hanging and heavy objects from the ignition key increases the amount of distance between a driver's knee and the key itself, decreasing opportunities for a driver to accidentally put any force upon the ignition key with his/her knee in such a manner as to cause the ignition switch to turn out of the "Run" position. The use of a single key also eliminates the possibility of an object hanging from the ignition key (e.g., a hang tag, lanyard, other keys, key fob, etc.) becoming inadvertently lodged in the steering wheel in such a manner that the ignition key could be pulled out of the "Run" position.

The new key or key head insert, which owners of recalled vehicles receive upon completion of an ignition switch repair, reduces the potential for other items attached to the ignition key to produce increased motion and force upon the ignition key. Such movement is typically associated with a slot design and can, under certain conditions, be great enough to create a force that could result in an unintentional ignition switch change out of the "Run" position.

History of GM Ignition Switch Testing Procedures

Prior to the 2014 ignition switch recall, GM did not have standard protocols in place to test for unintended ignition key rotation, though the company had ignition switch test procedures. Following its initial ignition switch recall in February 2014 (GM, 2014b), GM began to reorganize on a corporate level, resulting in the creation of a new systems engineering group. This group was tasked with providing high-level testing of the potential for an inadvertent change in the ignition switch position, with the ultimate goal

of preventing future ignition switch defects. The testing methodology (referred to as the "ignition switch tests") developed by this group will be assessed within this report.

To accurately begin to design tests for ignition switches, the company needed to be able to replicate the ignition switch unintentionally turning out of the "Run" position (what is known as the result) in such a manner that the test would be highly repeatable and representative of real-world driving conditions. Therefore, vehicles used for these ignition switch tests needed to remain in good repair for multiple rounds of testing. It was established by GM that the test vehicles could not be crashed or endure near-crash scenarios that would ultimately cause irreparable destruction to the vehicle. It should be understood that testing for every crash scenario is nearly impossible in terms of creating a standard testing scenario that is representative of all possible crash impacts a vehicle could experience. While some GM tests listed herein can recreate high-impact conditions, such as vaulting over a railroad crossing or hitting an abnormally large pothole at an increased speed, it is difficult to simulate all combinations of events experienced during a crash (e.g., a vault followed by impact with a stationary object). Even more difficult to determine is how vehicular occupants move during a crash, technically known as biomechanics associated with the crash event, due to wide-ranging variability relative to such factors as driver size, driving position, etc. Currently, GM ignition switch tests only account for vehicular occupants wearing a seat belt ("belted") since the company expects its drivers and passengers to obey all safety laws and assume proper precautions. In addition, accounting for all movement experienced by vehicular occupants not wearing a seat belt ("unbelted") during a crash scenario (particularly an off-road crash scenario) was deemed to be an extremely difficult scenario to accurately represent in GM tests.

With these testing restrictions in mind, the GM systems engineering group began to develop initial ignition switch tests. One such test involved the use of a four-post shaker, a piece of test equipment that includes four hydraulic actuators, or motors, on which the wheels of the test vehicle are placed. These motors are designed to simulate road surfaces and other forces experienced by the wheels of the vehicle. The four-post shakers (Figure 3) are typically used to measure new suspension systems and their durability. The shaker test was subsequently dismissed by GM for use in ignition switch testing because it only provided limited inertial inputs and did not match measurements found by GM in real-world driving scenarios.

Figure 3. Four-post shaker (photo courtesy of GM).

The GM systems engineering group also initially considered a railroad shipping simulation, which involved tying the test vehicles to a railroad car (Figure 4). This scenario would replicate the conditions experienced by the vehicle during transport. While this scenario could successfully cause a change in the ignition switch position (e.g., from “Run” to “Accessory”), the test was also not indicative of conditions experienced in the real world and was subsequently excluded by GM for use in its ignition switch testing.

Figure 4. GM railroad simulation (photo courtesy of GM).

The GM systems engineering group ultimately focused its attention on a series of three ignition switch tests: 1) Inertial, 2) Knee key, and 3) Hang tag. The inertial tests were

designed to objectively measure the potential of dynamic forces external and internal to the vehicle, such as different key masses and vehicle accelerations, to cause an unintended change in the ignition switch position. The knee-key test involved recruiting GM employees representing what the systems engineering group believed to be the 5th percentile female, the 50th percentile male, and the 99th percentile male to determine if those participants could make knee contact with the ignition key enough to rotate the ignition switch out of the "Run" position. Objective measurements were also taken during the knee-key test to determine the spatial relationship between a driver's knee and the ignition switch. The hang tag test was designed to determine if a key tag or other object hanging from the ignition key could become caught in the steering wheel in a horizontal position, thus providing a lever with which to unintentionally turn the ignition key out of the "Run" position. The hang tag test is generally considered to be much more subjective in nature than the inertial and knee-key tests.

Project Statement of Work

The three ignition switch tests (inertial, knee key, and hang tag) were developed by GM within a relatively quick timeframe (i.e., as of February 2014). GM, therefore, determined it required an objective and independent evaluation of these ignition switch tests for long-term use and viability. The company thus contracted with the Virginia Tech Transportation Institute (VTTI) during July 2014 for this purpose.

VTTI (herein referred to as the "VTTI project team") was tasked with providing a thorough, independent review of the GM testing methodology related to ignition switches and to identify any opportunities for enhancement. Specifically, the VTTI project team was asked to conduct a comprehensive and detailed technical assessment of the GM test methods, test procedures, and test data analysis techniques related to ignition switches. The scope of the project was focused on vehicle-, system-, and component-level tests that are being used to measure the robustness of the ignition switch to stay in the "Run" position when exposed to road-induced dynamic forces (i.e., the GM inertial test). The review also included the methodology that GM is using to determine the likelihood of a driver contacting an ignition key and unintentionally turning the key out of the "Run" position (i.e., the GM knee-key test).

The VTTI project team was contracted to evaluate:

- The engineering logic behind the testing and analysis methods/techniques used to validate the ignition switch at the component, system, and vehicle levels;
- The engineering rationale for determining test conditions (road forces, etc.); and
- The technical capability of the physical testing and analysis to validate a robust and safe component, system, and vehicle.

The VTTI project team was also asked to conduct employee interviews; observe the GM tests; and perform additional vehicle-, system-, or component-level testing (at GM or VTTI facilities) as required to meet the objectives of the project.

The result of the project was for the VTTI project team to recommend any enhancement(s) to GM testing, procedures, or analysis that would, based on the engineering judgment of the VTTI project team, be required to ensure a robust assessment of the ignition switch. Such results and recommendations are provided within this report.

It should be emphasized that the VTTI project team was asked to focus on the testing procedures developed by GM to validate its ignition switches. The team was not tasked, therefore, with evaluating other variables associated with GM's ignition switch recall, such as airbag deployment/non-deployment. The overall goal of this project was to provide a high-level review of the GM ignition switch testing procedures to help the company ensure such a recall is never warranted again.

About VTTI

VTTI has significant expertise, experience, resources, and capabilities unmatched within the realm of transportation safety. VTTI conducts research to save lives, time, money, and protect the environment. One of seven premier research institutes created by Virginia Tech to answer national challenges, VTTI is continually advancing transportation through innovation and has impacted public policy on national and international levels.

The VTTI Project Team

To evaluate the robustness of the GM ignition switch tests, VTTI assembled a team comprising Dr. Tom Dingus, director of the institute; Mr. Luke Neurauter, group leader of Connected & Advanced Vehicle Systems within the VTTI Center for Advanced Automotive Research; Dr. Kevin Kefauver, technical director for the National Tire Research Center and the Southern Virginia Vehicle Motion Labs, an affiliated company of VTTI; and Ms. Mindy Buchanan-King, research communications director at VTTI. Dr. Dingus is the Newport News Shipbuilding Professor of Civil and Environmental Engineering at Virginia Tech and is the president of VTT, LLC. He is center director of the Tier 1 Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC), which comprises a consortium of Virginia Tech/VTTI, the University of Virginia, and Morgan State University.

Since 1996, Dr. Dingus has managed the operations and research at VTTI, a multidisciplinary organization that annually conducts more than $40 million in sponsored research expenditures. Prior to joining Virginia Tech, Dr. Dingus was founding director of the National Center for Transportation Technology at the University of Idaho and was an associate director of the Center for Computer-Aided Design at the University of Iowa.

Dr. Dingus has conducted transportation safety and human factors research since 1984, including driver distraction and attention, the safety and usability of advanced in-vehicle devices, crash avoidance countermeasures, and truck driver fatigue. He has pioneered studies of naturalistic driving, which involve instrumenting cars, trucks, and motorcycles with unobtrusive video cameras and sophisticated instrumentation (e.g., radar)

designed to assess crash and near-crash causation and to test a variety of crash countermeasures. VTTI is currently leading such studies worldwide with more than 4,000 equipped vehicles.

Dr. Dingus was named a White House Champion of Change and was selected for his exemplary leadership in developing or implementing transportation technology solutions. Dr. Dingus is a Fellow of the Human Factors and Ergonomics Society (HFES) from which he has received several awards, including the A.R. Lauer Award for outstanding contributions to the field of safety. He has had the honor of testifying before a U.S. Congressional subcommittee (four times), the National Transportation Safety Board, and the National Council of State Legislatures about issues of driver distraction and attention.

Dr. Dingus has more than 220 technical publications and has managed more than $250 million in research funding thus far in his career. Notable projects for which Dr. Dingus has served as a principal investigator or program manager include the 100-Car Study sponsored by the National Highway Traffic Safety Administration (NHTSA), the Heavy Truck Drowsy Driver Warning System sponsored by NHTSA, and the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS) sponsored by the National Academy of Sciences (the Transportation Research Board).

As group leader for Connected & Advanced Vehicle Systems within the Center for Advanced Automotive Research at VTTI, Mr. Neurauter regularly oversees the development, organization, implementation, and overall management of transportation safety-related research projects. His work consists primarily of gathering and analyzing human factors-related data in an effort to evaluate prototype concepts and advanced technologies, including a range of active safety and connected-vehicle applications.

Mr. Neurauter typically directs efforts that are designed to assess advanced technology and/or active safety systems, paying particular attention to evaluating how drivers comprehend and interact with these systems through both controlled and naturalistic exposure. As part of these efforts, mental model development and driver response to both staged and naturally occurring events catered to the specific system being tested are routinely assessed and analyzed. Mr. Neurauter has been involved in more than 60 research projects during his time at VTTI, managing efforts varying in scale from small-sample controlled test-track studies to multi-year field operational tests.

Dr. Kevin Kefauver is the technical director for the National Tire Research Center and the Southern Virginia Vehicle Motion Labs, an affiliated company of VTTI. In this position, Dr. Kefauver uses a state-of-the-art force-and-moment tire test machine and a multi-post hydraulic shaker rig to solve technical issues and advance the state of the art in tire testing and tire modeling, vehicle dynamics testing, and vehicle dynamics modeling and simulation. Dr. Kefauver previously managed the seven-post hydraulic shaker laboratory for Dale Earnhardt Incorporated and worked in the Roadway Simulator laboratory at the U.S. Army Aberdeen Test Center. In these positions, Dr. Kefauver operated servo-hydraulic equipment for vehicle-in-the-loop simulation and tire

tests and developed test, equipment, and maintenance procedures for advanced vehicle testing and modeling. Dr. Kefauver received his B.S., M.S., and Ph.D. in mechanical engineering from the University of Maryland.

Ms. Mindy Buchanan-King is the research communications director for VTTI. Ms. Buchanan-King is responsible for working with the VTTI director to assist in coordinating activities surrounding research projects and strategic communications initiatives. In her role, she plans, schedules, conducts, and coordinates detailed tasks as part of major transportation safety and human factors engineering projects. She also contributes to research conceptualization, data collection, proposal and report development, and resource acquisition. Ms. Buchanan-King serves as the dedicated editor and writer for strategic communications and literary endeavors involving the director and is responsible for the production of marketing-related publications at the institute. She received her B.A. in mass communications from Emory & Henry College.

VTTI Experience, Sponsorship, and Resources

VTTI has more than 400 employees, of whom approximately one-half are devoted to driving safety. VTTI thus houses the largest group of driving safety researchers in the world. The institute has more than $40 million in annual research expenditures and has more than 200 active projects that range from truck driver fatigue to crash injury biomechanics to evaluating transportation infrastructure (e.g., lighting, pavement) and providing recommendations for improvement.

Since beginning operations 25 years ago, VTTI researchers have worked with myriad organizations to enhance transportation safety. From its inception, VTTI has worked with such U.S. Department of Transportation organizations as NHTSA, the Federal Motor Carrier Safety Administration (FMCSA), and the Federal Highway Administration. In addition, VTTI has major programs with the National Institutes of Health and the National Academy of Sciences, along with a number of sponsors that include state and local entities. VTTI also works with many private sponsors, including GM and seven other original equipment manufacturers (OEMs).

Figure 5 illustrates the breakdown of sponsors, partners, and clients at VTTI, as of fiscal year 2014. The majority of funding to the institute derives from federal organizations (70 percent), with subsequent funding coming from state and local agencies (9 percent) and private organizations such as GM and suppliers (21 percent). This breadth of sponsorship means that VTTI can work independently to improve the safety of every transportation user, from heavy-vehicle operators to light-vehicle drivers to motorcycle riders, bicyclists, and pedestrians.

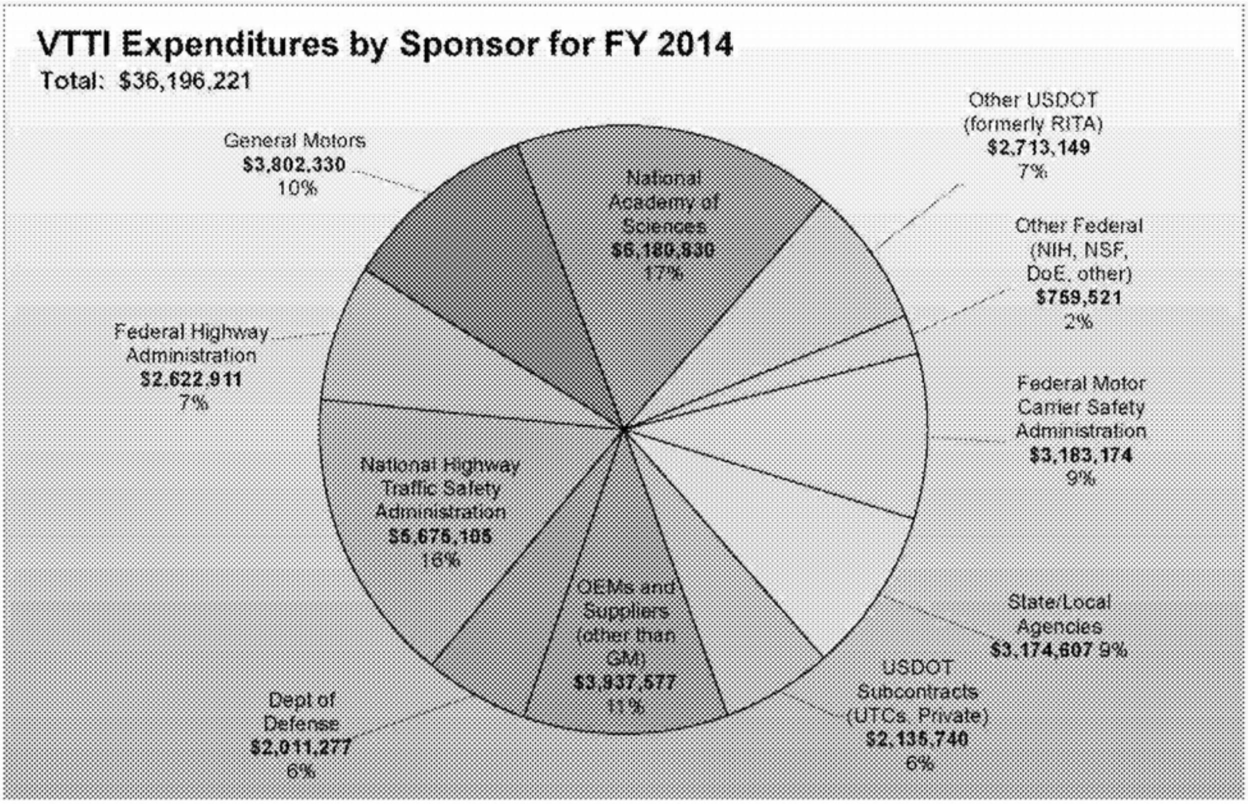


Figure 5. VTTI expenditures by sponsor, FY 2014.

Recent NHTSA projects led by VTTI include developing human factors guidelines for multiple connected-vehicle interfaces, evaluating the impact of lighting on driver performance, and collecting and analyzing data to understand heavy-vehicle drivers' responses to crash warning systems. Other federal projects conducted by VTTI include the development of a teen driving program during which real-time feedback is provided via a data system to the teen driver in an effort to mitigate erroneous driving behavior, with post-hoc information provided to the teen's guardian. VTTI researchers are also leading efforts to enhance the mobility of older drivers, to collaborate with other state agencies to improve pavement maintenance operations and sustainability efforts, and to create travel-time estimates that increase fuel efficiency and decrease negative environmental impacts.

VTTI research conducted through federal and state agency contracts have effected considerable change in the transportation community. For instance, VTTI studies have shown that looking away from the roadway just prior to the occurrence of an unexpected event is responsible for up to 90 percent of crash and near-crash events. The VTTI-led Driver Distraction in Commercial Vehicle Operations study found that texting while driving raises a heavy-truck driver's risk of a safety-critical event by 23 times. This statistic has been touted nationally, from the New York Times to the Ad Council to AT&T. The "23 times" message also helped lead the U.S. Department of Transportation to issue a call to end distracted driving. Currently, 41 states and the District of Columbia have banned text messaging for all drivers.

VTTI teen driving studies have shown that teens are four times more likely to get into a crash or near-crash while distracted than their adult counterparts. Teen fatalities are three times greater than adult fatalities, which is an important discovery of the prominence of a major causal factor among the teen driving population. VTTI studies have also shown that driver drowsiness is a significantly greater factor in crashes and near-crashes than was previously thought. Like heavy-truck drivers, light-vehicle drivers get into crashes and near-crashes between 15 percent and 20 percent of the time while at least moderately drowsy. Previous estimates were between 4 percent and 8 percent.

VTTI data provided FMCSA the information required to evaluate its hours-of-service regulations (e.g., off-duty time, on-duty time, breaks, re-start provisions). FMCSA adjusted its hours-of-service safety requirements, reducing by 12 the maximum number of hours a truck driver can work within a week (i.e., from 82 to 70 hours).

As part of its efforts to diversify its research portfolio, the institute also works with OEMs. For example, institute researchers recently completed the Light-vehicle Builds and Model Deployment Support for the Safety Pilot Program. This program was created by the U.S. Department of Transportation to demonstrate the feasibility of connected-vehicle safety technology in a real-world environment. As part of the program, VTTI was selected to provide support to the Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications 3—a consortium of eight vehicle manufacturers—in pre-model deployment testing, model deployment data collection, processing, storage and analysis, and post-model deployment evaluation. Data collected by VTTI for this program will provide valuable information towards understanding the potential for connected vehicles to improve the transportation system. VTTI also works with OEMs such as GM on proprietary efforts that include the development and evaluation of active safety systems installed in newer vehicle models. These systems include forward collision warning and lane-change warning, standard offerings that were first tested and/or developed at VTTI to ensure the systems increase driver safety and do not cause unintentional and hazardous distractions.

VTTI is also leading research endeavors in the field of connected and automated vehicles. The institute has conducted more than $30 million in connected-vehicle research and facility development since 2005. VTTI researchers are actively working with OEMs and suppliers on groundbreaking automated-vehicle studies and were recently awarded a federal contract with NHTSA at a maximum of $25 million during a five-year period to study automated-vehicle topics that range from human factors to cybersecurity.

At the core of VTTI research is its naturalistic driving studies, a research method pioneered by the institute nearly 15 years ago that is now being used on an international scale to study driver performance and behavior in a real-world environment, with the ultimate goal of ensuring transportation safety. Naturalistic studies involve equipping voluntary participants' vehicles with sophisticated cameras and inconspicuous instrumentation developed at VTTI. Using this method, researchers can gain a much more accurate understanding of driver error, distraction, fatigue, and impairment by

studying voluntary participants experiencing everyday driving environments with real consequences. The data collected during these naturalistic driving studies compose more than 2.5 petabytes, making VTTI home to close to 90 percent of naturalistic data in the world collected from more than 4,000 instrumented vehicles that range from tractor trailers to passenger cars to motorcycles. These vast amount of data available at VTTI can be continually mined to answer additional research questions asked by both internal and external clients.

The largest naturalistic driving study ever undertaken, the SHRP 2 NDS (Dingus et al., 2014), was recently completed by VTTI and other contractors for the National Academy of Sciences. The study resulted in more than 35 million miles of data collected from more than 3,000 participants. The SHRP 2 NDS database will be featured heavily in this report as its results facilitated the most direct comparison to data collected by GM during its ignition switch testing procedures. Therefore, more detailed information about the use of the SHRP 2 NDS database will follow later in this report.

To supplement its research endeavors, the institute has access to three major test facilities, discussed in Appendix A: the Virginia Smart Road located in Blacksburg, Va.; the Northern Virginia Connected-vehicle Test Bed in Fairfax County, Va.; and the Virginia International Raceway complex in Alton, Va.

Data Gathering and Understanding the Problem

Pre-assessment Efforts

Prior to traveling to GM to evaluate the company's ignition switch testing, the VTTI project team began by reviewing documents and records available to the public for the purpose of developing a full understanding of the ignition switch problem at GM. These sources included the investigative report conducted by Jenner & Block (commonly referred to as the Valukas report; Valukas, 2014), which outlines the chronology of the ignition switch recall. Documents from the April 2014 U.S. House of Representative Committee on Energy and Commerce hearing of the GM ignition switch recall were also studied to gain a more thorough understanding of related data, consumer complaints, possible vehicle dynamics and human factors issues relative to the ignition switch, and the mechanics of the ignition switch (Energy & Commerce, 2014). Media reports, specific consumer complaints about ignition switch issues available on the NHTSA SaferCar website (www.safercar.gov), and Internet forums documenting ignition switch issues experienced in both GM and non-GM vehicles were also reviewed.

Also prior to its visit to GM to experience the developed ignition switch tests, the VTTI project team borrowed two Chevrolet Cobalts included in the GM ignition switch recall (model years 2006 and 2010) from a nearby used car dealership to begin to understand the dimensions of the vehicle and driver position relative to the ignition switch. Both loaned vehicles previously received the new key repair (e.g., the keys had a hole design) and only had the dealership identification tag hanging from a larger key ring

attached to the ignition key. The VTTI project team did not add any weight or length to these ignition keys while in possession of the loaned vehicles.

To begin to understand possible inertial effects relative to the recalled Chevrolet Cobalts, members of the VTTI project team drove the two loaned Cobalts across two passes of a sloped section of the Smart Road (e.g., one pass along a downgrade at a lower speed [~25 mph], followed by a turnaround and one pass back up the same area at a faster speed [~40 mph]). The drivers also tried to subjectively determine the likelihood of making knee contact with the ignition key to move the ignition switch out of the "Run" position. However, the drivers were unable to get into a normal driving position that would ensure knee contact with the ignition key. Therefore, they manually turned the ignition from "Run" to "Off" during the aforementioned test drives to determine the ease with which the test vehicles could be handled if power was lost to the engine. Both vehicles could be successfully maneuvered to a safe stop following a loss of engine power under normal driving conditions.

While still in possession of the two loaned Cobalts, the VTTI project team then gathered two employees they believed most closely aligned to the 5th and 99th percentile female and male, respectively. It should be noted that, because of the limited amount of time the team had to use the loaned Cobalts, this exercise was performed in a relatively short timeframe as a way of gaining perspective into driver positioning relative to the ignition switch. The female stood at 5'1"; the male stood at 6'4". Both were asked to adjust the steering wheel and seat to their normal driving positions while the loaned vehicles were parked at the institute. These percentile representatives were then asked to demonstrate a series of leg movements: transition from the gas pedal to the brake pedal, how the driver would place his/her foot upon the brake pedal during normal driving, how the driver would place his/her foot upon the gas pedal during normal driving, and the driver's normal foot placement upon moving into cruise control mode. These movements were chosen as they illustrate cases during which the knee may be elevated, thus increasing the possibility of a knee-key interaction with the ignition key. Figure 6 and Figure 7 illustrate the VTTI drivers' positions relative to the ignition switch in the loaned Cobalts. Both the male and female percentile representatives found the ignition key relatively easy to rotate out of the "Run" position, but both noted such manipulation of the key could only be achieved in an abnormal driving position.

Figure 6. Male VTTI driver; driver's right foot is placed on gas pedal.

Figure 7. Female VTTI driver; driver's right foot is placed on gas pedal.

The VTTI project team also conducted an independent "key chain rodeo" in an attempt to determine the normal distribution, or the mean and standard deviation, of key weights and key chain lengths across a sampling of drivers. This key chain analysis was conducted using a random sample of 60 respondents (33 males, 27 females) on-site at the institute. Appendix B charts the weight, measurement, and key head design of each respondent. Though performed using a small sample size, the results (Figure 8) from this rodeo found that the worst-case scenarios in terms of key weight and length were 8 oz. (0.5 lb) and 20 in. (52 cm), respectively. This provided a reference point for the heaviest weight/longest length compared to the more "normal" key weights and lengths (i.e., normal distribution).

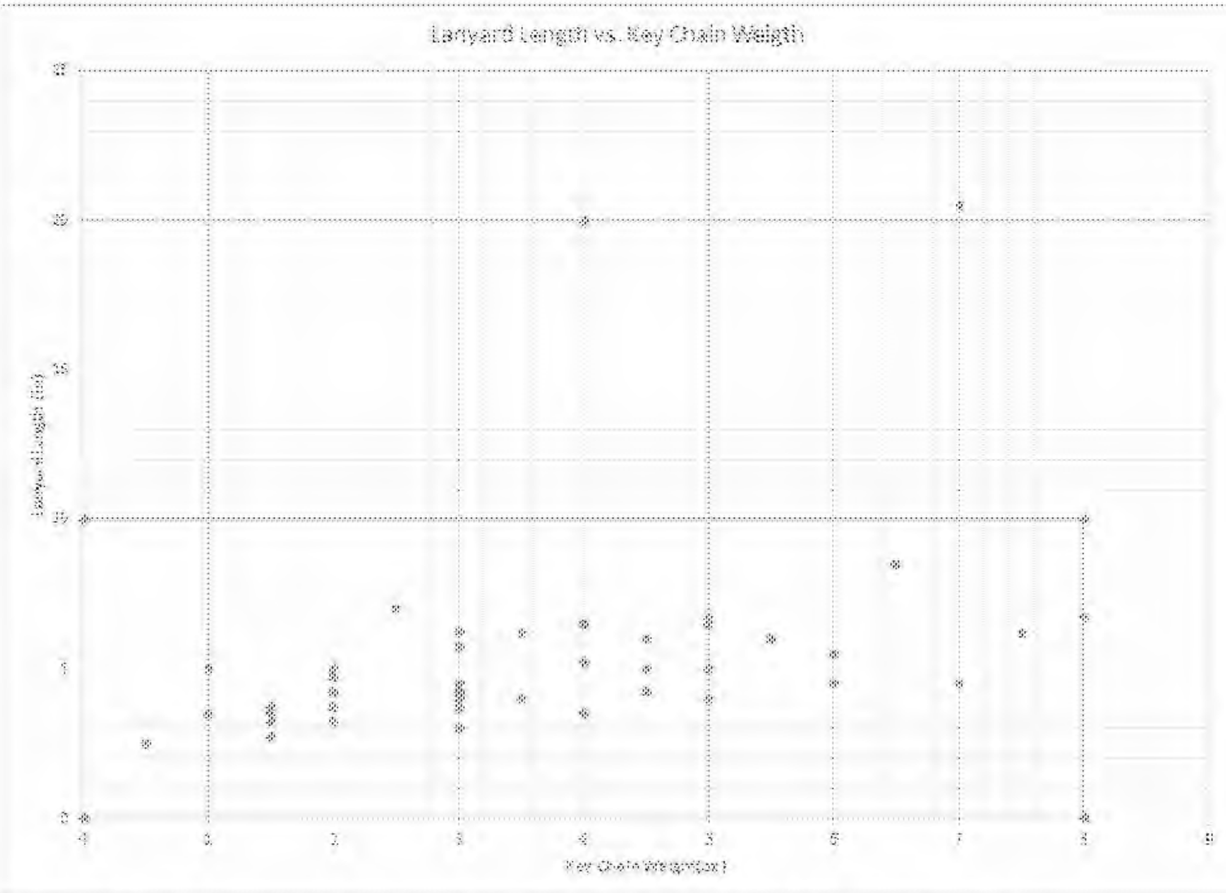


Figure 8. VTTI "key chain rodeo" data: lanyard length vs. key chain weight.

This preliminary background work was performed at a higher level prior to the VTTI project team's visit to the GM Milford Proving Grounds (MPG) as a way of understanding the design of the GM ignition switch and to begin determining vehicle and driver dynamics that could impact the ignition switch component and potentially result in an unintentional change in the ignition switch position. This analysis assisted the VTTI project team in developing a preliminary set of questions and data needs prior to receiving a first-hand tutorial of the GM ignition switch test process at the MPG.

Assessment Efforts

Upon arrival at the GM MPG during July 2014, the VTTI project team was provided first-hand access to ignition switch testing and resources, to the extent feasible. While GM provided sufficient access to its test data, it should be noted that not all data were available due to current litigation processes. However, the data made readily available to the VTTI project team were comprehensive enough for the team to feel it could confidently determine the robustness and validity of the GM ignition switch tests (i.e., inertial, knee-key, and hang tag testing). The VTTI project team's initial experience with each of these tests is summarized below. Immediately following this section is a summary of draft protocols developed by GM for each test.

Inertial Test

To understand the inertial tests conducted by the GM systems engineering group, the VTTI project team received demonstrations of the tools used to measure torque, the different key weights used for testing, and the MPG driving events conducted using sample vehicles.

The GM systems engineering group measures torque across the entire ignition system. This system-level torque is important because, when the ignition switch component is installed in the vehicle, the resulting system-level torque is greater than the ignition switch torque itself. GM also uses static and dynamic torque measurements. Static torque measurements are made by measuring the torque required to slowly move the ignition switch from “Run” to “Accessory.” These measurements are performed using a handheld torque meter (Figure 9). Dynamic torque measurements are made by measuring the torque required to quickly move the switch from “Run” to “Accessory.” Dynamic torque is measured using a bench-top fixture built specifically for this purpose (Figure 10).

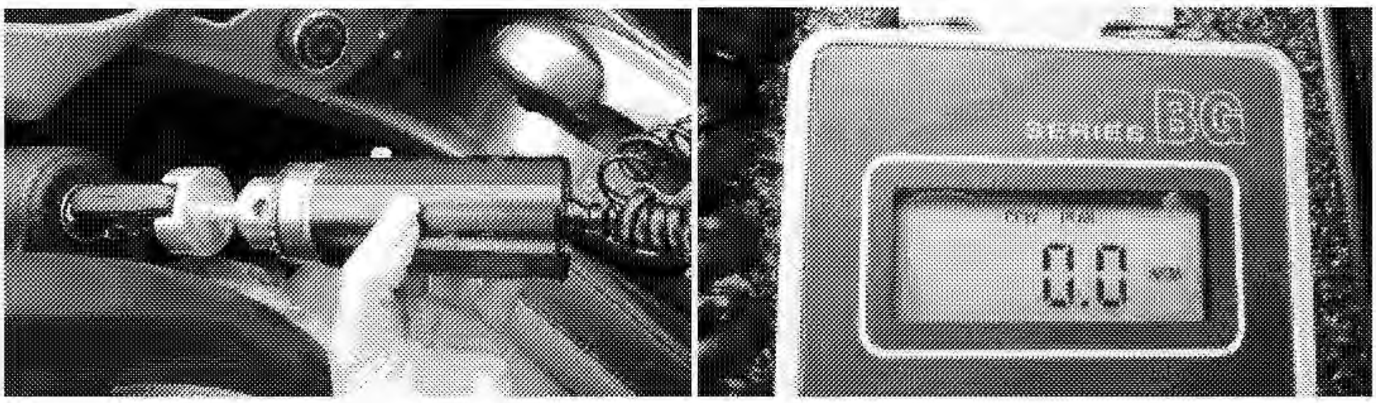


Figure 9. Handheld torque meter (left) and meter reading screen (right). Photos courtesy of GM.

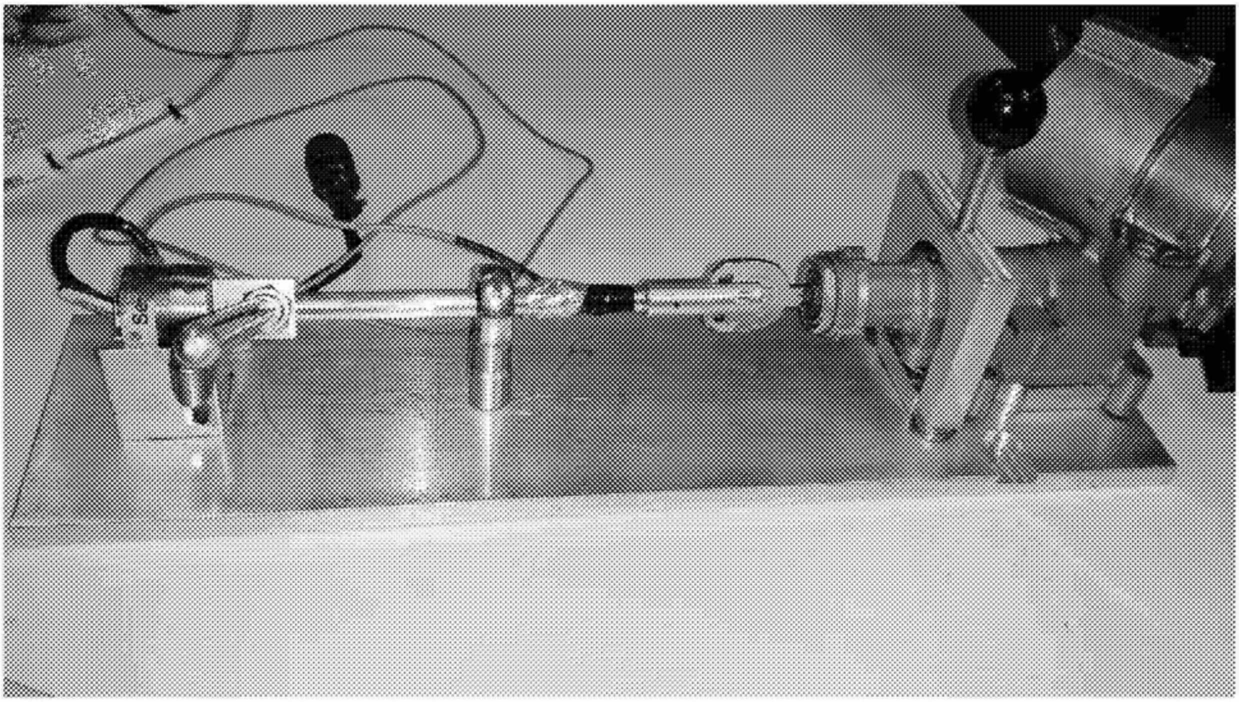


Figure 10. Dynamic ignition switch torque testing device (photo courtesy of GM).

The VTTI project team then traveled in three cars affected by the ignition switch recall (two Chevrolet Cobalts and one Saturn Ion) across eight inertial events at the GM MPG (see *Overview of GM Ignition Switch Testing Procedures* for specific information about these eight events). While test vehicles used for GM's inertial testing are normally equipped with accelerometers designed to measure impactful forces such as acceleration, or g-force, such equipment was not used for these sample drives performed with the VTTI project team as they fell outside the proper testing protocols. The sample drives were instead used to demonstrate each GM MPG event used for inertial testing.

To further assist in its understanding of how inertial issues were classified at GM, the VTTI project team asked GM for access to the test results of vehicles evaluated during inertial tests. GM provided the following sample of test vehicle data; it should be noted that these data were previously collected by the GM systems engineering group and were not available for public distribution:

- Pontiac Grand Prix (model years 2004 and 2008)
- Oldsmobile Alero (model years 1999 and 2003)
- Chevrolet Malibu (model years 2002 [2 vehicles], 2005 Classic, and 2006 LT)
- Pontiac Grand Am (model years 1999, 2001, 2002, and 2005)
- Chevrolet Impala (model years 2000, 2003, 2004, 2007 [2 vehicles], and 2010)
- Cadillac DTS (model years 2004 [then known as a Deville] and 2007)
- Buick Lacrosse (model year 2006)
- Buick Lucerne (model year 2007)

Data were also provided for the following GM vehicles, though the results for these vehicles did not include all information relative to the inertial tests. Again, it should be noted that these data were previously collected by the GM systems engineering group and were not available for public distribution:

- Saturn Ion (model year 2007)
- Chevrolet HHR (model year 2008)
- Chevrolet Cobalt (model year 2009 [2 vehicles])

GM also tested non-GM vehicles during inertial tests; resulting data included the following vehicles. These data were requested by the VTTI project team for further clarification of any inertial issues experienced across the automotive industry. These data were previously collected by the GM systems engineering group and were not available for public distribution:

- Ford F-150 (model year 2013)
- Honda Civic (model year 2012)
- Volkswagen Passat (model year 2012)
- Ford Focus (model year 2012)

Knee-key Test

The VTTI project team was able to subjectively evaluate the GM knee-key test in several recalled GM vehicles; the team also requested to conduct independent knee-key tests within non-GM vehicles as a means of benchmarking knee-key potential across a range of vehicle makes and models.

Percentile representatives (5^{th} female, 50^{th} and 99^{th} males, in terms of height) used by GM demonstrated the system engineering group's characterization of knee-key plausibility. The representatives sat in the car and adjusted their seats until they were in their normal driving positions, then they attempted to make physical contact with the ignition key using their knees. The representatives demonstrated the GM ranking system for knee-key possibility (e.g., easy/medium/difficult to turn the ignition key; whether the driving position was normal/abnormal). During this independent testing evaluation, VTTI asked the representative drivers to also demonstrate their normal movements when transitioning from the gas pedal to the brake pedal, as well as what position the representative driver would be in upon moving into the cruise control mode. Members of the VTTI project team were also invited to try to make knee contact in sample GM vehicles as a means of further understanding the in-vehicle structure, driver positioning, and the force required to achieve an ignition switch position change. Figure 11 through Figure 13 demonstrate knee-key testing performed by GM.

Figure 11. Female (5th percentile) knee-key evaluation (photo courtesy of GM).

Figure 12. Male (50th percentile) knee-key evaluation (photo courtesy of GM).

Figure 13. Male (99th percentile) knee-key evaluation (photo courtesy of GM).

To further assist in its understanding of how knee-key issues were classified at GM, the VTTI project team asked GM for access to the test results of vehicles evaluated during knee-key tests. GM provided the following sample of test vehicle data; it should be noted that these data were previously collected by the GM systems engineering group and were not available for public distribution:

- Pontiac Grand Prix (model years 2004 and 2008)
- Oldsmobile Alero (model years 1999 and 2003)
- Chevrolet Malibu (model years 2002 [2 vehicles], 2005 Classic, and 2006 LT Classic)
- Pontiac Grand Am (model years 1999, 2001, 2002, and 2005)
- Chevrolet Impala (model years 2000, 2003, 2004, 2007 [2 vehicles], and 2010)
- Cadillac DTS (model years 2004 [then known as a Deville] and 2007)
- Buick Lacrosse (model year 2006)
- Buick Lucerne (model year 2007)

The VTTI project team also requested to conduct an independent assessment of non-GM vehicles available on location at the MPG. This evaluation was performed by the

VTTI project team as it felt it was important to perform comparative analyses using a range of vehicle samples. The VTTI project team was escorted to various MPG lots and randomly sampled 16 vehicles from Ford, Honda, Toyota, Nissan, BMW, Hyundai, Volkswagen, and Dodge for its independent knee-key evaluation. During this assessment, the VTTI project team used the same parameters as GM to rank knee-key plausibility (e.g., easy/medium/difficult to turn the ignition key; whether the driving position was normal/abnormal). Based upon these independent evaluations, it was determined that other non-GM vehicles may experience knee-key issues. The VTTI project team subsequently asked GM to run its standard knee-key test using the following test vehicles:

- 2013 Ford 150
- 2012 Honda Civic
- 2012 Volkswagen Passat
- 2012 Ford Focus
- 2012 Honda CR-V
- 2013 Dodge Ram
- 2013 Toyota RAV-4
- 2013 Hyundai Santa Fe
- 2006 BMW 330ci

<u>Hang Tag Test</u>

The GM hang tag test is used to determine if hang tags or other objects present on a key ring can somehow become lodged within the steering wheel in such a way as to unintentionally turn the ignition switch away from the “Run” position. It is anticipated that this entanglement could occur when the hang tag, or other objects present on the key chain (e.g., other keys, lanyards, fobs, etc.), begin to swing due to inherent vehicle dynamics associated with both normal and off-road (i.e., road departure) driving events. A great enough swing due to inertial effects could cause the hang tag or other object hanging from the ignition key to interact with the steering wheel area and become lodged in a manner that could potentially cause an inadvertent change in the ignition switch position.

As GM demonstrated to the VTTI project team, a hang tag event could involve the interaction of several factors, including tag length, steering wheel spoke configuration, presence of raised areas on the wheel (e.g., leather that includes stitching), ignition key location, and ignition key orientation. A hang tag scenario (Figure 14) is also more likely to occur during large steering wheel movements, such as a left- or right-hand turn, though such movements are generally made at a slower speed.

Figure 14. Demonstration of a possible hang tag scenario (photo courtesy of GM).

Though fewer complaints were entered to a dealer for hang tag issues compared to knee-key and inertial issues, GM chose to design an assessment test using this parameter. While the original project statement of work did not include an assessment of the hang tag test, the VTTI project team was given leeway to evaluate the robustness of the hang tag test and to provide recommendations.

Upon request, GM provided the VTTI project team with the following list of consumer complaints categorized as either an emerging issue related to a hang tag scenario or a potential hang tag scenario:

- 2014 Chevrolet Equinox (hang tag complaint logged by a consumer in GM-internal Speak Up for Safety [SUFS] data)
- Chevrolet Equinox (hang tag complaint logged by a consumer in SUFS data)
- 2003 Yukon XL Denali (emerging issue of a hang tag complaint)
- K2XX (logged field complaint)
- 2007 GMC Yukon (potential emerging issue)
- 2008 Saturn Astra (potential emerging issue)

Overview of GM Ignition Switch Testing Procedures

GM has developed draft protocols for each of its three ignition switch tests. Those protocols are summarized below.

Inertial Test

For the inertial testing procedure, GM personnel are first instructed to measure the torque, or the force required to move the ignition switch position. GM uses a torque meter (Figure 9) placed at the key head and rotated at a rate at which the sample frequency captures the peak torque (measured in Newton centimeters [Ncm]). When measurement data are required, GM also instruments its inertial test vehicles with a triaxial accelerometer that collects proper acceleration data at a frequency of 1,024 Hz, which is then filtered at 120 Hz. This measure of frequency is used by GM as it is derived from the SAE J211 standard.

The test vehicles are then driven across eight events at GM MPG:

1. Ride and handling loop at posted speeds (the loop contains high-speed “S” curves, railroad crossings, and chatter bumps)
2. Belgian blocks (Figure 15)
3. 50^{th} percentile pothole at 25 mph (Figure 16)
4. 75^{th} to 85^{th} percentile pothole at 25 mph (Figure 17)
5. A replica of a cubilete (e.g., a high-severity road found in Mexico that comprises mortared river rocks) driven at 10 to 15 mph (Figure 18)
6. Panic stops conducted on a smooth and level road surface; the test vehicles are accelerated to 10 to 15 mph, then a complete and rapid brake pedal application is made (Figure 19)
7. The ride and handling loop with a “coast down” from 55 to 45 mph on the chatter bumps, which are a series of evenly spaced bumps (Figure 20a)
8. The ride and handling loop angled railroad crossing taken at 60 to 80 mph; the crossing is elevated and is not perpendicular to the road direction (Figure 20b)

Figure 15. GM MPG Belgian blocks (photo courtesy of GM).

Figure 16. GM MPG 50th percentile pothole (photo courtesy of GM).

Figure 17. GM MPG 75th to 85th percentile pothole (photo courtesy of GM).

Figure 18. GM MPG cubilete (photo courtesy of GM).

Figure 19. Panic stops performed at the GM MPG (photo courtesy of GM).

(a) (b)

Figure 20. GM MPG ride and handling loop chatter bumps (a) and angled railroad crossing (b). Photos courtesy of GM.

The GM MPG driving events are performed beginning with a key weight of 0.7 lb (Figure 21) hanging from the ignition key, a mass used by GM to mimic force experienced during near-accident scenarios. As discussed previously, GM is unable to recreate accelerations experienced in near-crash or crash conditions due to the necessity of maintaining the integrity of its test vehicles. Therefore, GM engineers increased the mass of the keys used during inertial tests to produce the same amount of force experienced during extreme driving conditions (e.g., off-road driving). The 0.7 lb key mass also correlates to more extreme key chain weights and measurements found among real-world drivers. Similarly to the VTTI key chain rodeo (see *Data Gathering and Understanding the Problem* for more information), GM measured the length and weight of keys available from 502 drivers surveyed at shopping locations. GM's determination of the worst-case scenario in terms of key weight closely aligned with that of what VTTI discovered during its smaller sample rodeo (0.61 lb and 0.5 lb, respectively). A detailed comparison of the GM and VTTI key weight/length charts is provided in the section titled *Assessing the GM Inertial Test*.

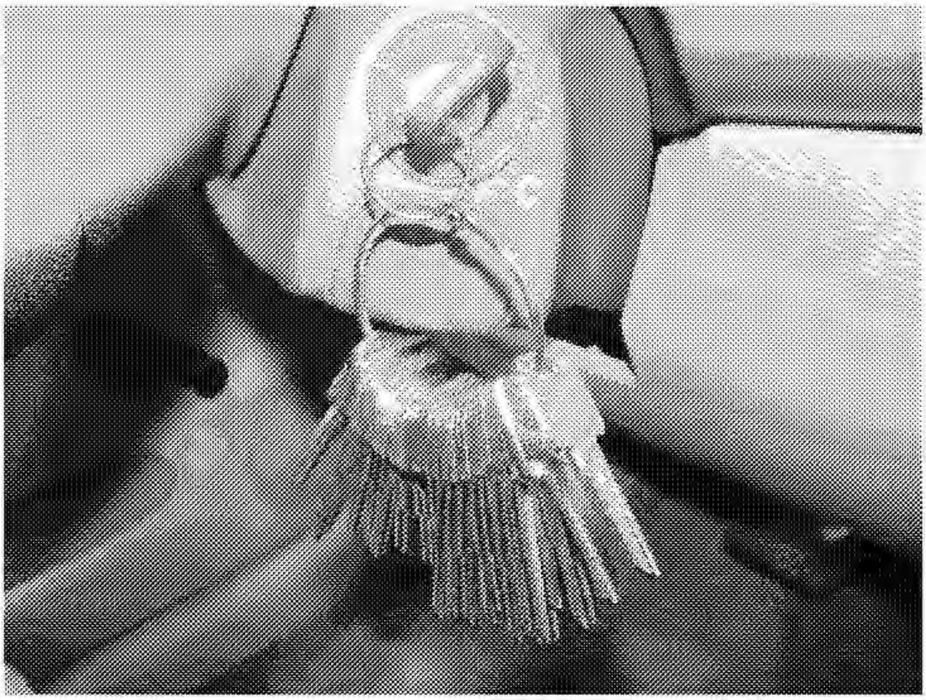


Figure 21. GM key testing (0.7 lb in slot key head design). Photo courtesy of GM.

For each of the eight driving events conducted on the MPG, GM notates the key weight (in lb), if any, at which an unintended key rotation occurs in the ignition switch (e.g., from "Run" to "Accessory"). GM begins with the 0.7 lb key mass attached to a determined key ring configuration (Table 1). The first round of inertial testing uses the original key head design (e.g., a slot; Figure 21) since it represents the worst-case scenario in terms of creating extra force and movement upon the ignition key that could potentially cause an unintentional change in the ignition switch position. The test vehicles are then driven across the GM MPG events. If the car inadvertently switches from the "Run" position, this is marked on a spreadsheet to denote the test and the key weight at which the change in the ignition switch position occurred. Table 2 is a sample representation of the key weight rankings made across the eight GM MPG events, where P denotes pass (i.e., no unintentional rotation occurred in the ignition switch position) and F denotes fail (i.e., an unintentional rotation occurred in the ignition switch position). If the initial key weight (e.g., 0.7 lb) causes an unintended ignition switch position change, then key weights are incrementally tested (up to 0.2 lb) across the GM MPG events until the ignition switch does not change position.

Table 1. Key Weight and Key Chain Configuration for GM Inertial Test.

0.7 lb (on 50 mm ID ring)
0.63 lb (on 50 mm ID ring)
0.55 lb (on 50 mm ID ring)
0.4 lb (on 35 mm ID ring)
0.3 lb (on 35 mm ID ring)
0.2 lb (on 25 mm ID ring)

Table 2. Example of Key Mass Rankings across GM MPG Events.

	Ride & Handling Loop (posted speed)	Ride & Handling Loop (coast down)	Ride & Handling Loop (railroad crossing)	Belgian Blocks	Cubilete	Panic Stop	50th Percentile Pothole	75th-85th Percentile Pothole
0.7 lb	P	P	F	P	P	P	P	P
0.61 lb			F					P
0.5 lb			P					P
0.4 lb								
0.3 lb								
0.2 lb								

To determine the use of a hole key head design versus a slot key head design in effectively eliminating the potential for an unintentional ignition switch position change, the eight GM MPG events are then run with the heaviest (0.7 lb) mass of keys placed in the same ignition key configuration (Table 1), this time using a hole key head design achieved using an insert (Figure 22). It should be noted that, based upon the data provided to the VTTI project team, all inserts passed the inertial test at the heaviest weight. That is, by switching to a hole design in the key head, the heaviest key weight did not rotate the ignition key from "Run" to "Accessory" or "Off."

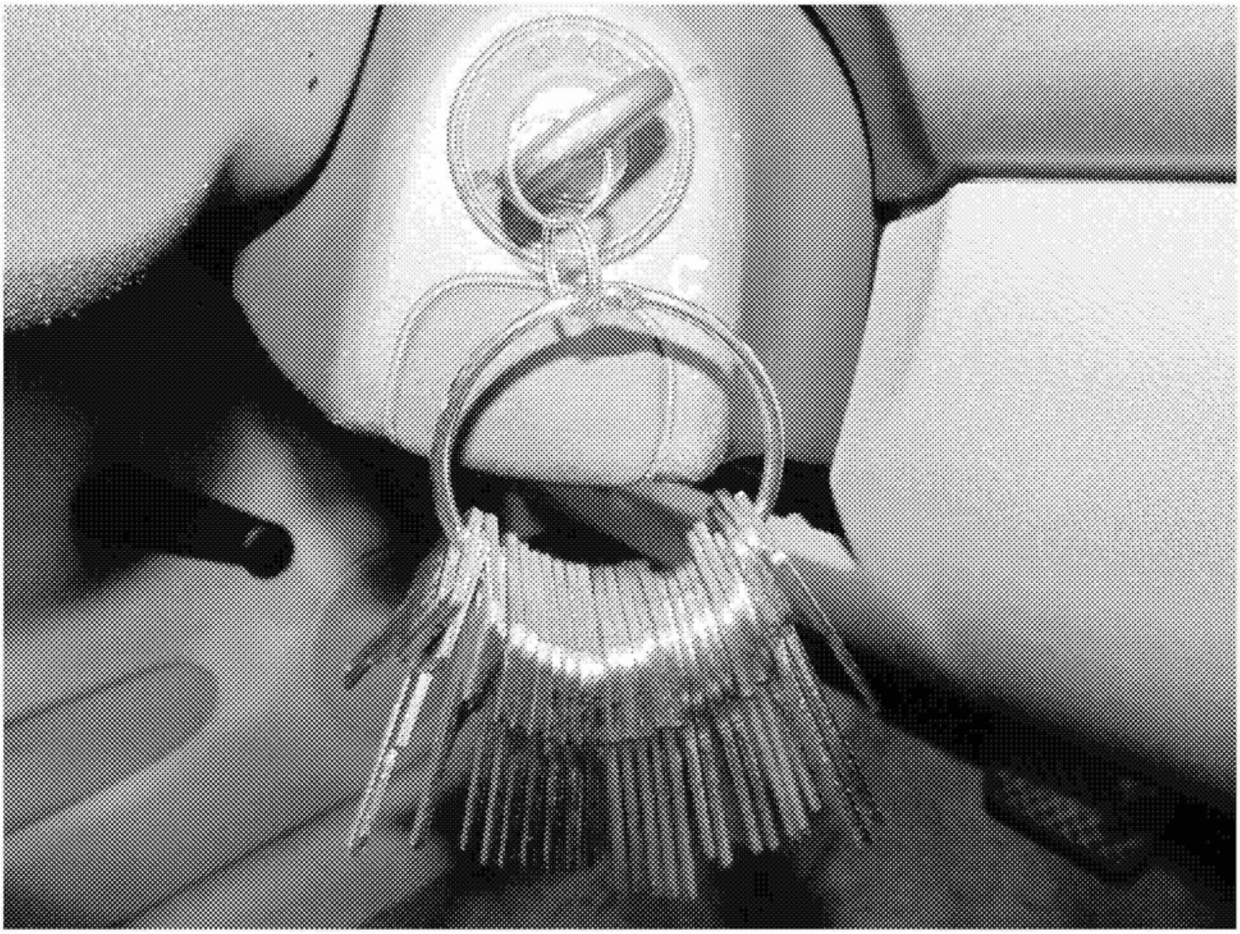


Figure 22. Hole key head design with 0.7 lb key weight (photo courtesy of GM).

Because GM uses a greater key mass during its inertial test, the need for a maximum key chain length is eliminated. That is, if the key mass is increased, the key chain length can be decreased by the same percentage, and the resultant torque at the ignition switch will remain the same. The VTTI project team verified this assumption during testing of its predictive model developed for this project (see *Assessing the GM Inertial Test)*.

Knee-key Test

As mentioned previously, GM selected individuals within the company representing what its engineers determined to be the 5th percentile female, 50th percentile male, and 99th percentile male in terms of height. These individuals, or percentile representatives, are asked to sit in the sample vehicles and adjust their seats and steering wheels to their normal driving positions. These individuals are then asked to try to make contact with the ignition key using their knees, rating the ease of the key rotation (easy/medium/difficult) and the driving position (normal/abnormal) required to create a change in the ignition switch position. Key rotation ease and the driving position required are rated using both key head designs (e.g., slot and insert with the hole).

Objective measurements for knee-key potential are also performed in each sample vehicle. With the percentile representative's right foot placed on the brake, GM measures the distance from the driver's knee to the ignition key at a straight-line distance (knee to the bottom of the key) and the distance from the driver's knee to the key fob at a straight-line distance (knee to the bottom of the key fob; Figure 23).

Figure 23. Sample knee-key measurement made using a 99th percentile male representative (photo courtesy of GM).

Hang Tag Test

To determine the ease with which a hang tag item could make contact with the steering wheel in such a way that a lever would be created to inadvertently change the ignition switch position, GM performed a subjective evaluation using two types of hang tags. GM personnel were first asked to manipulate a key chain with a stiffer insert (Figure 24) and/or key fob to create a potential interference between the key and the steering column while the ignition switch was in "Run." The likelihood of an ignition switch change occurring was then evaluated based on the number of movements required to create the event and the location of the interference if it could be created. These two steps were then repeated using a standard tag that was more flexible.

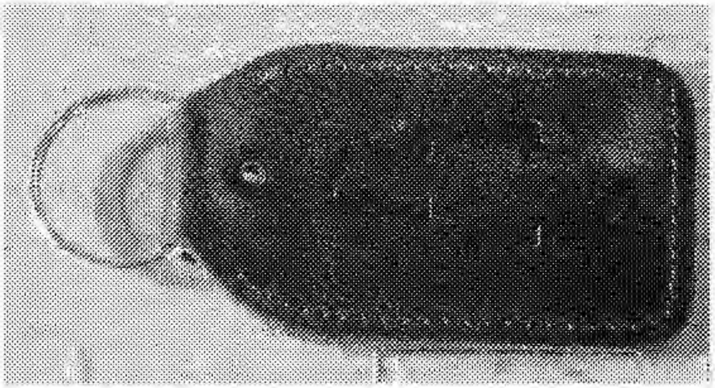


Figure 24. Stiff leather hang tag.

Evaluating and Validating GM Ignition Switch Testing

Following its first-hand experience at the GM MPG, the VTTI project team determined several methods for evaluating and validating the measurements and procedures used by the GM systems engineering group for ignition switch testing. With access to vast amounts of naturalistic driving data and experience in vehicle modeling and evaluating human factors relative to the vehicle, the VTTI project team could use its experience and expertise to answer the purpose of this project: to conduct a comprehensive and detailed technical assessment of the GM test methods, test procedures, and test data analysis techniques related to ignition switches.

Naturalistic Driving Study Instrumentation and Data

As previously stated, VTTI has access to close to 90 percent of naturalistic driving data in the world. Such data are collected from naturalistic driving studies, a research method pioneered by VTTI during the 100-Car Naturalistic Driving Study sponsored by NHTSA. Naturalistic driving studies involve instrumenting voluntary participants' vehicles with unobtrusive cameras, radars, and other sensors known collectively as a data acquisition system (DAS). Participants are asked to drive as they normally would in real-world conditions. That is, VTTI does not place personnel in the vehicle with the participants, nor do participants drive in a closed test environment. There is evidence (Lee et al., 2007) to suggest that voluntary participants in these studies drive as they normally would within a few hours of DAS instrumentation. Therefore, actual driver behavior and performance are captured during these studies; the drivers do not compensate their behavior or performance based on the vehicle instrumentation. To date, VTTI has instrumented 4,000 vehicles traveling in the U.S., Canada, Australia, and China.

The DAS, which is created by the VTTI Center for Technology Development, has been designed to collect and store large amounts of continuous detailed data from the driving environment, including video, vehicle network information, and additional sensor information that can include radar, GPS, and acceleration.

The data collected from various onboard systems are processed and stored in the DAS, which is similar to a "black box" unit found in commercial airplanes. The DAS features are configurable and typically include:

- An arm-based core with video processing on a digital signal processor chip;
- Additional sensors, such as accelerometers and gyroscopes;
- Video with H.264 video/audio compression and multi-channel binary data synchronization;
- GPS;
- Doppler-based front and rear radar;
- Controller area network 2.0B, VPW, PWM, and ISO vehicle network interfaces; and
- Removable, high-capacity, shock-resistant hard drives for data retrieval.

Via its cameras, the DAS can collect information about a range of variables. These cameras record multiple views that can include forward, rearward, and internal views (such as over-the-shoulder, face, and pedal areas). Across the sensor package, data parameters can be customized to include such variables as:

- Vehicle network data, such as speed, airbag deployment, brake use, throttle position, turn signaling, and many other elements;
- Environmental factors, such as weather, lighting, glare, and temperature;
- Presence of nearby objects and their relative speed obtained via radar and optical technologies; and
- Other data, such as sound, vibration, acceleration, and turning rate.

The DAS runs custom data acquisition software using a Linux operating system and communicates with a distributed data acquisition network. Other electronic subsystems that use their own microprocessors are applied in an instrumented vehicle to interface with the driver or for specific functions, such as facilitating communication with the existing vehicle onboard diagnostic network.

Each subsystem functions as a node on the data acquisition network. This system configuration maximizes flexibility while minimizing the physical size of the system. Although capable of expansion to 120 nodes, current instrumented vehicles at VTTI are generally configured with 10 nodes. This process of distributed data acquisition results in an adaptable and maintainable hardware data collection system.

Customized machine-vision software incorporated into the VTTI DAS hardware can include lane-tracking information and the driver's head position.

DAS units can also feature cellular machine-to-machine technology that disseminates software upgrades to installed units; transmits events of interest (such as crashes) to project servers; and collects DAS function reports, or what are dubbed "health checks." These combined capabilities ensure that important information is being relayed and that the DAS is functioning properly.

While the 100-Car Naturalistic Driving Study was the first of its kind, VTTI and other contractors recently concluded data collection for the largest naturalistic driving study ever undertaken: the SHRP 2 NDS. This database covers more than 35 million miles of data from more than 3,000 participants. The resulting data capture a breadth of vehicle and dynamic information, including acceleration measured across lateral (side-to-side), vertical (up-and-down), and longitudinal (forward-moving) directions; ignition state (e.g., when the ignition switch moved out of the "Run" position); and GPS location. The sophisticated cameras located throughout the participants' vehicles provide a wealth of information about the driver state (e.g., fatigued, impaired, etc.), road and weather conditions, and in-vehicle events. The SHRP 2 NDS cameras capture four views: the driver's face, an over-the-shoulder view of the driver (e.g., the steering wheel, ignition switch, driver's lower body position, etc.), and forward and rearward views of the roadway (Figure 25). The resulting videos are analyzed by a team of data reductionists located on-site at VTTI within the Center for Data Reduction and Analysis Support. Reductionists are trained to review videos and flag events of interest, such as crashes and near-crashes. As of the writing of this report, 700 crashes and 5,000 near-crashes have been identified in the entire SHRP 2 NDS database (analyses are still ongoing).

Figure 25. Screenshot of in-vehicle video available in the SHRP 2 NDS (clockwise, from upper left): driver's face view, forward view, rearward view, over-the-shoulder view.

During normal driving, a data point is recorded in the SHRP 2 NDS every 0.1 seconds (i.e., at a sample rate of 10 Hz) when the ignition switch is in the "Run" position. The SHRP 2 NDS database can be queried, or searched, for parameters of interest within

the data; video data can provide a visual point of reference for all events captured within each query. Therefore, the query will output events that match the initial search parameters, and trained data reductionists review the accompanying video for each event to determine what happened and to omit any false alarms.

For the purposes of this project, the SHRP 2 NDS database was the logical first step in the VTTI project team's creation of a normal distribution, or standard, of parameters that could be used to verify the GM ignition switch tests. In other words, the VTTI project team used the database to begin to determine via real-world information if the GM ignition switch tests are robust.

During this project, the SHRP 2 NDS database was queried in search of cases during which the ignition state was unintentionally altered either due to inertial, knee-key, or hang tag factors. To accomplish this goal, a basic query was used to flag trip files in the database during which the ignition state moved out of the "Run" position adjacent to a speed trace greater than or equal to 5 mph. It should be noted that the speed variable in the SHRP 2 NDS is captured either from the vehicle network or through the GPS. It should also be noted that the ignition signal is captured at various access points on differing vehicles, thus affecting the timing of the ignition state variable in some SHRP 2 cases. The ignition state variable in the SHRP 2 NDS also generally classifies a loss to the engine power as "Off." That is, the database does not differentiate between the "Off" or "Accessory" mode. To account for each of these factors, the VTTI project team used a liberal query to capture all possible events during which an unintentional change in the ignition switch position occurred. Due to this approach, the majority of reviewed events included drivers purposefully turning the ignition off (e.g., at the end of a trip). However, the VTTI project team decided not to further refine the query at the risk of missing any true events that illustrated an unintentional change in the ignition switch position.

A SHRP 2 NDS query was also made to capture high acceleration readings that occurred prior to the change in ignition state. The VTTI project team specifically examined peaks in pitch and up/down accelerations made within five seconds prior to the ignition changing out of the "Run" position. Such readings could indicate a relatively high-impact event (e.g., a large bump, off-road scenario, etc.) that resulted in an inadvertent change in the ignition switch position. This approach did result in finding relevant inertial events involving severe road undulations (e.g., railroad crossing).

Videos from the aforementioned queried trips were then reviewed to determine if the ignition was turned off manually (e.g., at the end of a trip) or if a change in the ignition state was registered that could be due to an inertial, hang tag, or knee-key event. Queries for this project were limited to GM vehicles only. The SHRP 2 NDS included 519 GM vehicles across 10 makes and 81 different models, as illustrated in Table 3 and Table 4. More than half of these makes (51.3 percent, or 266/519) were Chevrolets, followed by Pontiac (15.2 percent, or 79/519) and Saturn (11.4 percent, or 59/519) rounding out the top three representative GM vehicles in the SHRP 2 NDS database. By model, the top three representatives were the Chevrolet Malibu (60), Impala (41), and Cobalt (39) at 11.6 percent, 7.9 percent, and 7.5 percent, respectively. The vehicles

highlighted within Table 3 and Table 4 were impacted by the 2014 ignition switch-related recalls (GM, 2014b). Of the approximately five million total trip files available in the SHRP 2 NDS database, more than 800,000 included GM vehicles. Of these 800,000 trip files, more than 600,000 included the ignition-source variable, meaning data were available that indicated when the ignition was in the "Run" position and when it moved out of the "Run" position.

Table 3. SHRP 2 GM Vehicle Fleet (Buick, Cadillac, Chevrolet, and Geo)

Make	Model	Model Year																									Total	% of Total
		1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013		
Buick	Century												1	1	4	3											9	2%
	Enclave																						1				1	0%
	LaCrosse																	3		1			1	1	1		7	1%
	LeSabre							1	1		1		2	1													6	1%
	Lucerne																		3	1	1	3	4				12	2%
	Park Avenue													2													2	0%
	Regal				1			1					1			2								1			6	1%
	Rendezvous															1		1									2	0%
Cadillac	CTS																1		1		2	1	1				6	1%
	DeVille												1														1	0%
	DTS																					1	1	1			3	1%
	Escalade																			2		2					4	1%
	SRX																						1		1		2	0%
	STS							1								1			1								3	1%
Chevrolet	Aveo																	3	1		4	2	1	2			13	3%
	Blazer											1															1	0%
	Camaro																								1		1	0%
	Caprice	1																									1	0%
	Cavalier										2	3	3	4	3	2	5										22	4%
	Cobalt																	8	4	10	10	6	1				39	7.5%
	Colorado																						1				1	0%
	Cruze																							11	12	1	24	5%
	Equinox																			3	2	1	2	4		2	14	3%
	HHR																			1	1	1	1				4	1%
	Impala												3	1	3	2	1		8	4	12	2	2	3			41	7.9%
	Lumina				1					1	1		1	1													5	1%
	Malibu											1		4	3	5	4	5	9	4	11	7	4	3			60	11.6%
	Monte Carlo												1							2							3	1%
	S10						1			1			2														4	1%
	Silverado		1									1			2	1			1	1	3	3	1	2	1		17	3%
	Sonic																								1		1	0%
	Spark																									1	1	0%
	Tahoe													2											1		3	1%
	Trailblazer														1	1		1	1	1							5	1%
	Traverse																					2	1				3	1%
	Venture													1	1		1										3	1%
Geo	Metro								1																		1	0%
	Prizm							1			1	1															3	1%
	Tracker												1	1													2	0%

Indicates Recalled Vehicle and Specific Model Years Impacted

Table 4. SHRP 2 GM Vehicle Fleet (GMC, Oldsmobile, Pontiac, SAAB, Saturn, and Suzuki)

Make	Model	Model Year																									Total	% of Total
		1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013		
GMC	Acadia																			2	1			1	1		5	1%
	Envoy																3										3	1%
	Jimmy								1	1	1																3	1%
	Sierra						1			1											2		1	2			7	1%
	Sonoma													1													1	0%
	Terrain																						1	1			2	0%
	Yukon														1					1			2	1			5	1%
Oldsmobile	Alero												1		2												3	1%
	Aurora											1		1													2	0%
	Bravada													1													1	0%
	Cutlass										1																1	0%
	Eighty-Eight									1																	1	0%
Pontiac	Aztek														1		1										2	0%
	G5																				1	1					2	0%
	G6																	3	8	6	3	8					28	5%
	Grand Am											1	4	2	1	4		1									13	3%
	Grand Prix										1	1		1	1		3	2			1						10	2%
	Montana																2										2	0%
	Sunfire								1				1		1	1		1									5	1%
	Torrent																		1	2	3						6	1%
	Vibe															3				2	1	5					11	2%
SAAB	9-3																		1								1	0%
Saturn	Astra																				1						1	0%
	Aura																			1	2	4					7	1%
	Ion															2	5	1	2	8							18	3%
	L200															1											1	0%
	L300													1	1												2	0%
	LS1												2			1											3	1%
	LW														1												1	0%
	Outlook																					1					1	0%
	SC1												1														1	0%
	SC2									1																	1	0%
	SL											1	1	1													3	1%
	SL1													1													1	0%
	SL2								1			1			1												3	1%
	SW					1																					1	0%
	Vue														1	4	1		3		5	1					15	3%
Suzuki	Aerio																1										1	0%
	Forenza																1				1						2	0%
	SX4																				5						5	1%
	Verona																1										1	0%
	Vitara														1												1	0%

Indicates Recalled Vehicle and Specific Model Years Impacted

As will be discussed later within this report, five inertial events and four knee-key events were discovered in the SHRP 2 NDS database. No hang tag events were observed in the SHRP 2 NDS database. It should be noted that analyses of inertial, knee-key, and hang tag events in the SHRP 2 NDS database were limited. That is, a full-scale analysis exceeded the scope of this effort, so it was not possible to review all flagged events based on the query outputs. As such, cases found and discussed within this report are

based on an incomplete review of all possible returned events. However, focusing the SHRP 2 NDS review upon events with high speeds and acceleration measures was more likely to reveal events of interest for this project, thus priority was given for flagged events that met these criteria.

The following sections detail more fully how the SHRP 2 NDS database was used to evaluate each GM ignition switch test (i.e., inertial, knee key, and hang tag).

ASSESSING THE GM INERTIAL TEST

Overview

GM has identified manufactured vehicles that have steering column- and dash-mounted ignition switch systems that may experience an unintended ignition key rotation due to inertial effects experienced under certain driving conditions and ignition key configurations, thus moving the ignition switch position from "Run" to "Accessory" or "Off." The purpose of this section of the report is to evaluate the GM methodology and procedures developed to understand and mitigate an unintended ignition key rotation due to inertial effects experienced by the vehicle.

Inertial effects are vehicle body-level accelerations that can cause forces and moments on the ignition switch system, thus causing an unintended ignition key rotation. Under normal driving conditions, the vehicle will experience inertial effects in the longitudinal direction (forward driving), lateral direction (side to side), and vertical direction (up and down). The inertial accelerations can occur individually or simultaneously in all three directions. When coupled with these inertial accelerations, key ring configurations that include a large mass hanging from the ignition key may cause large inertial forces to act upon the ignition key, potentially resulting in an unintended change in the ignition switch position.

To properly evaluate the inertial effects experienced in GM vehicles, the VTTI project team undertook seven subtasks: 1) Document the GM procedures currently used to identify unintended ignition switch rotation in vehicles due to inertial effects; 2) Develop a predictive model to simulate inertial effects, with results compared to GM MPG inertial data to determine the validity of the model; 3) Compare inertial accelerations experienced by vehicles at the GM MPG with inertial accelerations defined in more than 1.2 million trips from the SHRP 2 NDS database that represent real-world driving events; 4) Validate the use of key torque measurements used by GM; 5) Perform a statistical analysis of consumer key rings and key chains using VTTI and GM data; 6) Determine the effects of key ring binding on unintended ignition key rotation; and 7) Review the SHRP 2 NDS database for any cases during which an unintentional change in the ignition switch position occurred due to inertial effects.

Subtask 1: GM Inertial Tests

As described previously, GM has developed a test to evaluate how inertial effects could potentially cause an unintended ignition key rotation. The test includes hanging a 0.7 lb mass of keys from the ignition key ring and running the vehicle across eight GM MPG events. It is then observed if unintended ignition key rotation occurs. If unintended key rotation occurs, the vehicle is graded as fail, and the mass is incrementally reduced (e.g., from 0.7 to 0.61 lb, up until 0.2 lb) until the key rotation does not occur. The following three properties of the ignition switch are also recorded and are combined with

the pass/fail grades for key rotation to determine the performance of a sample vehicle during the inertial test:

- Static system-level torque required to rotate the ignition key from "Run" to "Accessory";
- Minimum and maximum steering column angles; and
- Key angle in the "Run" position.

To accurately test inertial effects, GM drives sample vehicles across the following MPG events, beginning with the 0.7 lb mass hanging from the ignition key:

- Belgian block at posted speed limit; this is a cobblestone surface with both low and high acceleration content.
- Cubilete at posted speed limit; this is a rocky road surface found in Mexico and comprises mortared river rocks.
- Ride and handling loop at posted speed; this is a general road surface that has events that may be encountered during normal driving, including chatter bumps, high-speed cornering with bumps, a railroad crossing, and general bump inputs throughout.
- Ride and handling loop with an angled railroad crossing taken between 60 to 80 mph.
- Ride and handling loop with chatter bumps taken at a coast down from 55 to 45 mph.
- Pothole #1 at 25 mph; this is a pothole that represents a 50th percentile pothole.
- Pothole #2 at 25 mph; this is a pothole that represents a 75th to 85th percentile pothole.
- Panic stop following an acceleration between 10 to 15 mph; this is a test during which the brake is pushed rapidly and held until the vehicle comes to a stop. If the vehicle is equipped with an anti-lock braking system (ABS), the brake is pushed rapidly enough to enable the ABS.

It should be noted that there are two different ride and handling loops performed: 1) The ride and handling loop at posted speed and 2) The ride and handling loop that includes the angled railroad crossing taken at increased speeds and the coast down across the chatter bumps. Therefore, the GM MPG events discussed herein will make reference to the first loop as Ride and Handling Loop #1, and the second loop will be collectively named Ride and Handling Loop #2.

For this subtask, GM provided VTTI with sample data for four GM vehicles tested according to the methodology presented above. The four vehicles represented were:

1. 2007 Cadillac DTS
2. 2007 Chevrolet Impala
3. 2008 Pontiac Grand Prix
4. 2005 Chevrolet Cobalt

The results of the qualitative field testing for these vehicles can be found in Table 5.

Table 5. GM MPG Data for Four GM Vehicles.

Event	2007 Cadillac DTS	2007 Chevrolet Impala	2008 Pontiac Grand Prix	2005 Chevrolet Cobalt
Pothole 1	P	F	P	F
Pothole 2	F	F	P	? (F)
Belgian Block	P	P	P	P
Ride and Handling 1	P	P	P	F
Ride and Handling 2	P	P	P	F
Cubilete	P	P	P	P
Panic Stop	P	N/A	P	P

Where F (fail) indicates that an unintended ignition key rotation occurred, and P (pass) means no unintended ignition key rotation occurred. GM also provided VTTI with the associated longitudinal, lateral, and vertical accelerations taken at the steering column of these four vehicles. Figure 26, Figure 28, Figure 30, Figure 32, Figure 34, Figure 36, and Figure 38 illustrate the vertical and longitudinal acceleration data recorded at each time step (i.e., time history) for the four sample GM vehicles provided. The statistical characteristics of the time history can be analyzed by calculating the cumulative percentage of the acceleration data. The cumulative percentage is calculated by recording the total number of occurrences of each acceleration in the time history, dividing the number of occurrences of each acceleration by the total number of acceleration occurrences, and plotting (in ascending order) the cumulative sum of the percentage of each acceleration occurrence relative to the total number of points in the time history versus the acceleration value. The x-axis of the resulting plot ranges from the minimum to the maximum acceleration value; the y-axis of the resulting plot ranges from 0 percent to 100 percent. Ninety-nine percent of the data will be acceleration values between 0.5 percent and 99.5 percent. Figure 27, Figure 29, Figure 31, Figure 33, Figure 35, Figure 37, and Figure 39 illustrate the cumulative percentage plots for the respective time histories.

Figure 26 and Figure 28 are the time histories of the vertical and longitudinal accelerations taken at the steering column of each sample vehicle for Pothole #1 and Pothole #2, respectively. Note the large spikes in vertical and longitudinal accelerations as the vehicle passes through the pothole event, with low accelerations occurring most everywhere else during these events. This implies that the minimum and maximum accelerations experienced during the pothole events may be the appropriate event characteristics to use when evaluating ignition key responses to inertial effects. The cumulative percentage plots in Figure 27 and Figure 29 reinforce this determination since the acceleration values in the 1-99 percent range are small relative to the 0-1 percent and 99-100 percent values.

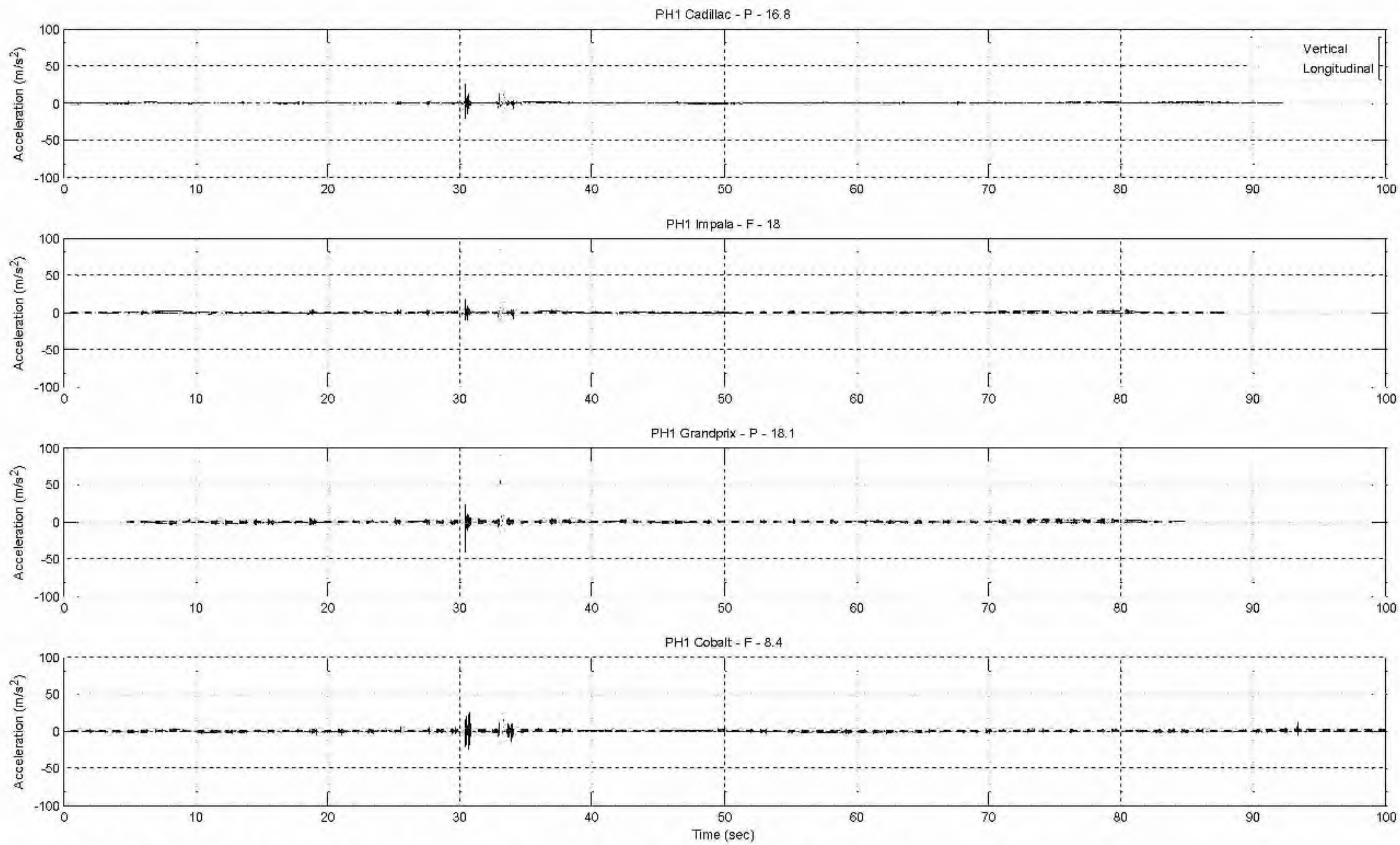


Figure 26. Vertical and longitudinal accelerations for Pothole #1 test.

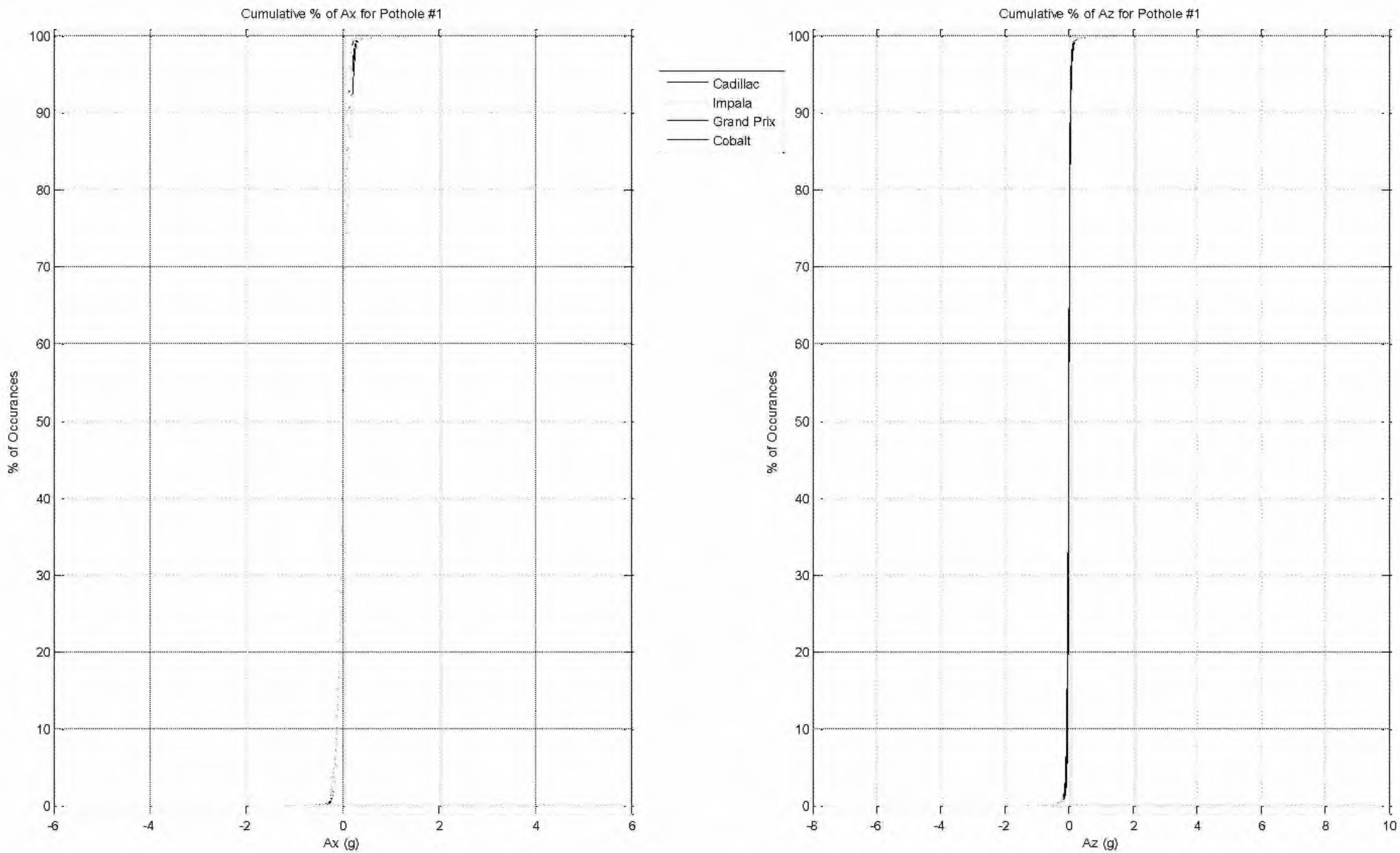


Figure 27. Cumulative percentage of vertical and longitudinal accelerations for Pothole #1 test.

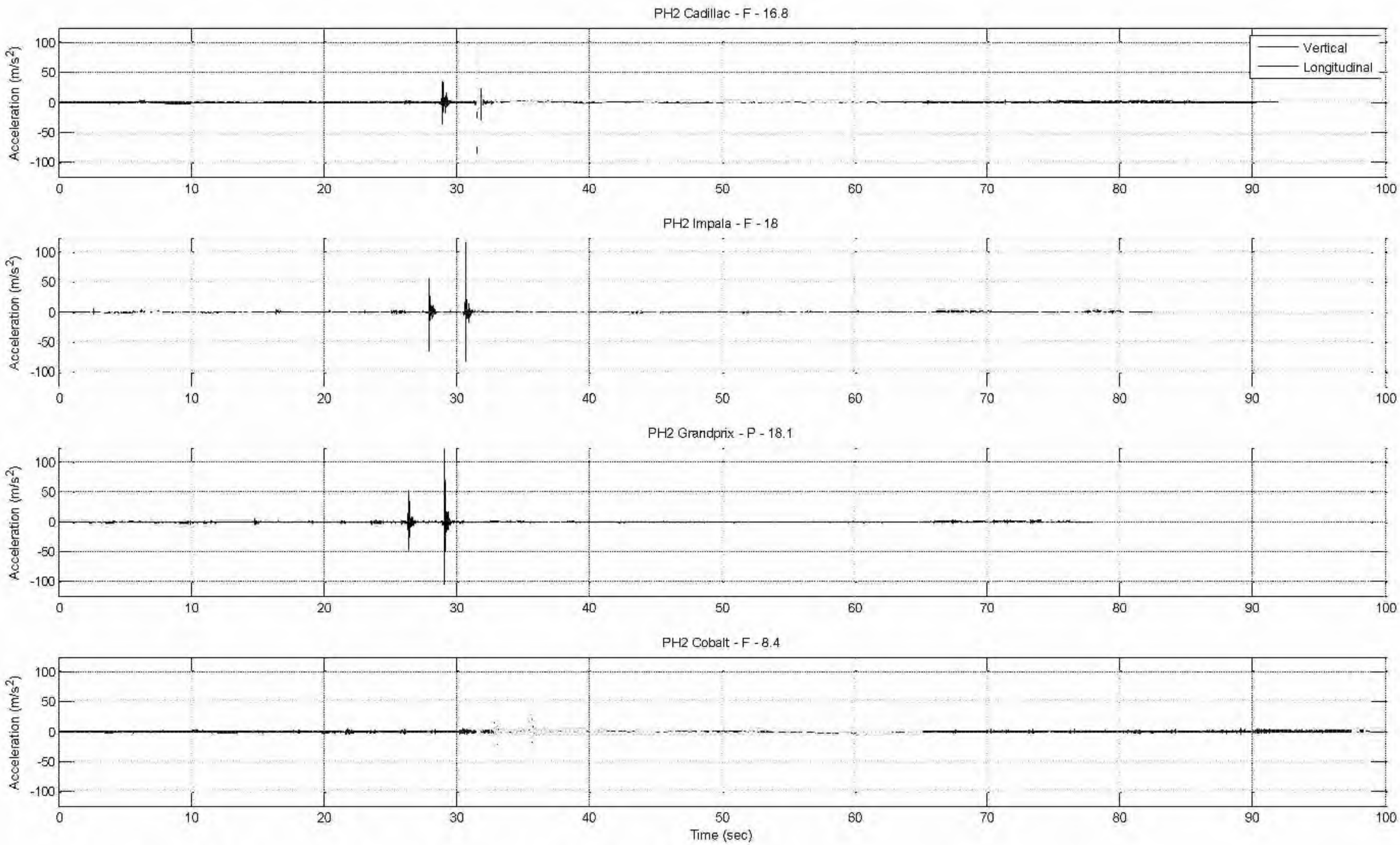


Figure 28. Vertical and longitudinal accelerations of Pothole #2 test.

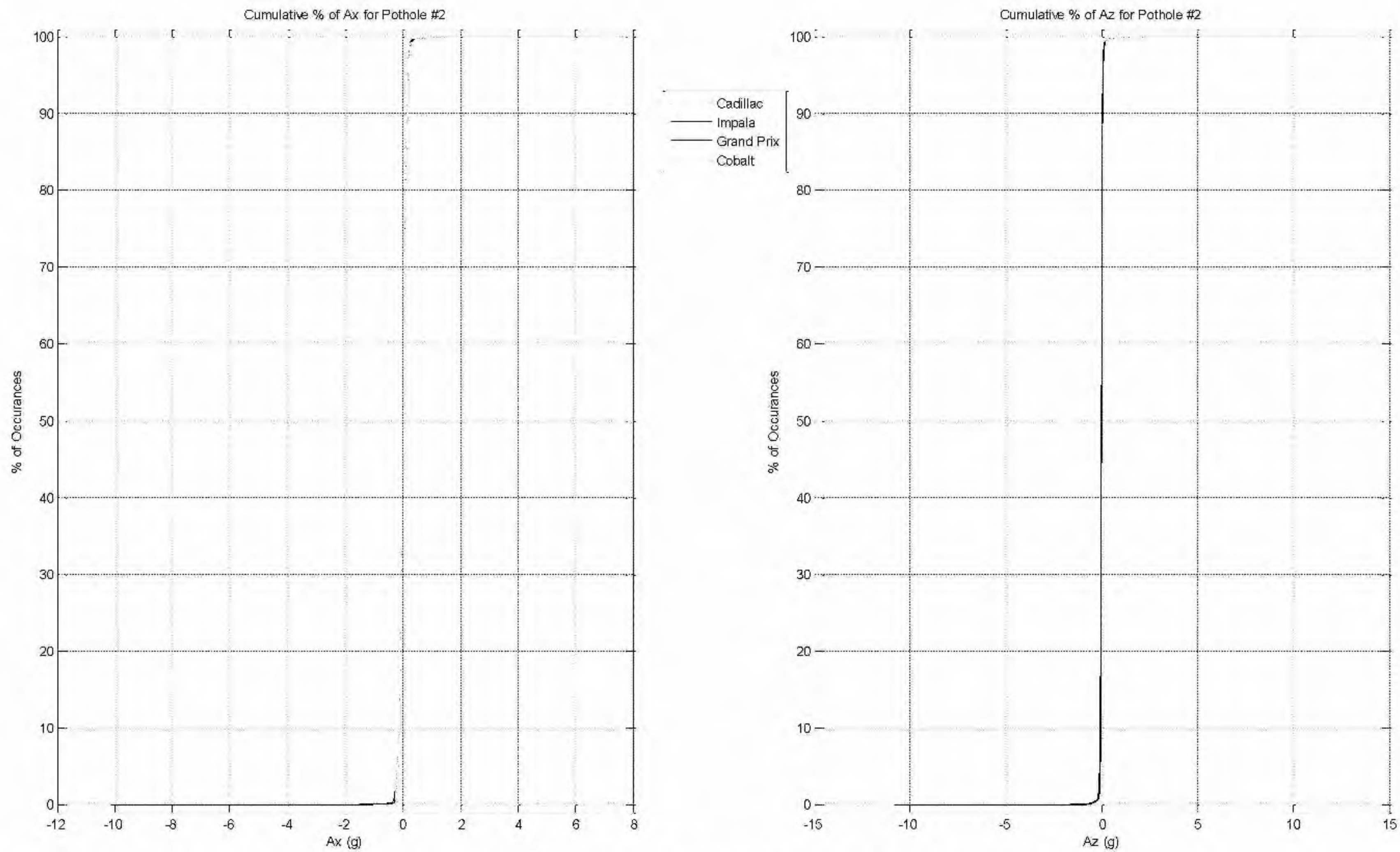


Figure 29. Cumulative percentage of vertical and longitudinal accelerations for Pothole #2 test.

The Belgian Block response time histories and cumulative frequency plots are found in Figure 30 and Figure 31, respectively. The time-history data (Figure 30) and the cumulative frequency data (Figure 31) both indicate that this GM MPG event course is rich in acceleration content. The cumulative frequency plot shows more acceleration content in the 1-99 percent range compared to the pothole tests, but the peak accelerations within the Belgian Block event are smaller. The Belgian Block event also shows how the vehicle and steering column responses can vary from vehicle to vehicle. For instance, the 2005 Chevrolet Cobalt has more acceleration content in both the longitudinal and vertical directions compared to the other three sample vehicles.

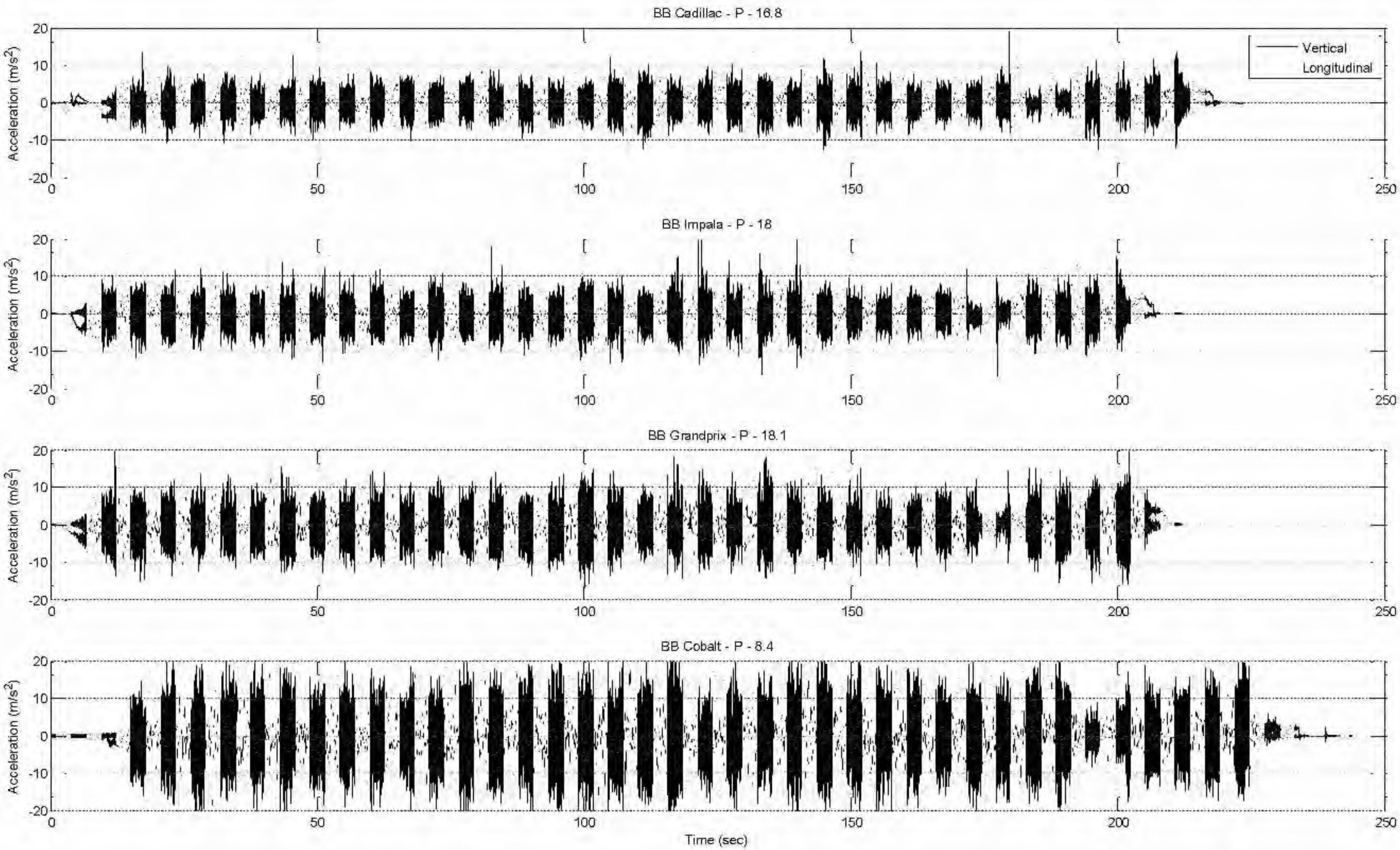


Figure 30. Vertical and longitudinal accelerations of Belgian Block test.

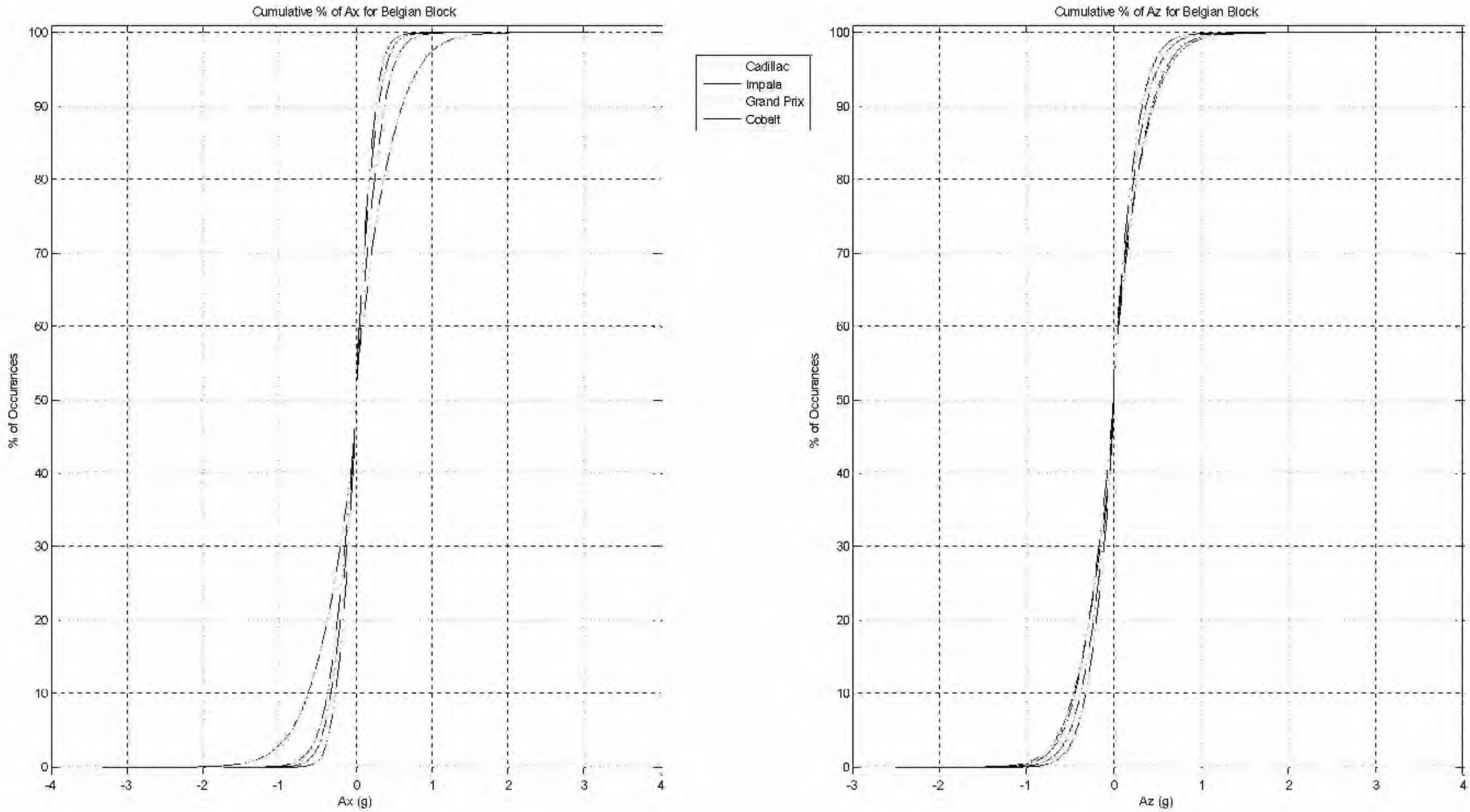


Figure 31. Cumulative percentage of vertical and longitudinal accelerations for Belgian Block test.

The Ride and Handling Loops #1 and #2 depicted in Figure 32 through Figure 35 produce general multi-acceleration inputs to the vehicle and steering column. The time-history data (Figure 32 and Figure 34) show general acceleration content and spikes in the data. The cumulative percentage plots (Figure 33 and Figure 35) reinforce this determination because both plots show more acceleration content in the 1-99 percent range than the Pothole #1 and #2 data and less acceleration content than the Belgian Block event. The spikes in data during Ride and Handling Loops #1 and #2 produce 0-1 percent and 99-100 percent acceleration responses that fall between the Pothole data and the Belgian Block data. As the speed is increased during the second lap of the Ride and Handling event, the outlier acceleration responses increase in magnitude as the impacts experienced during this event produce greater accelerations to the vehicle.

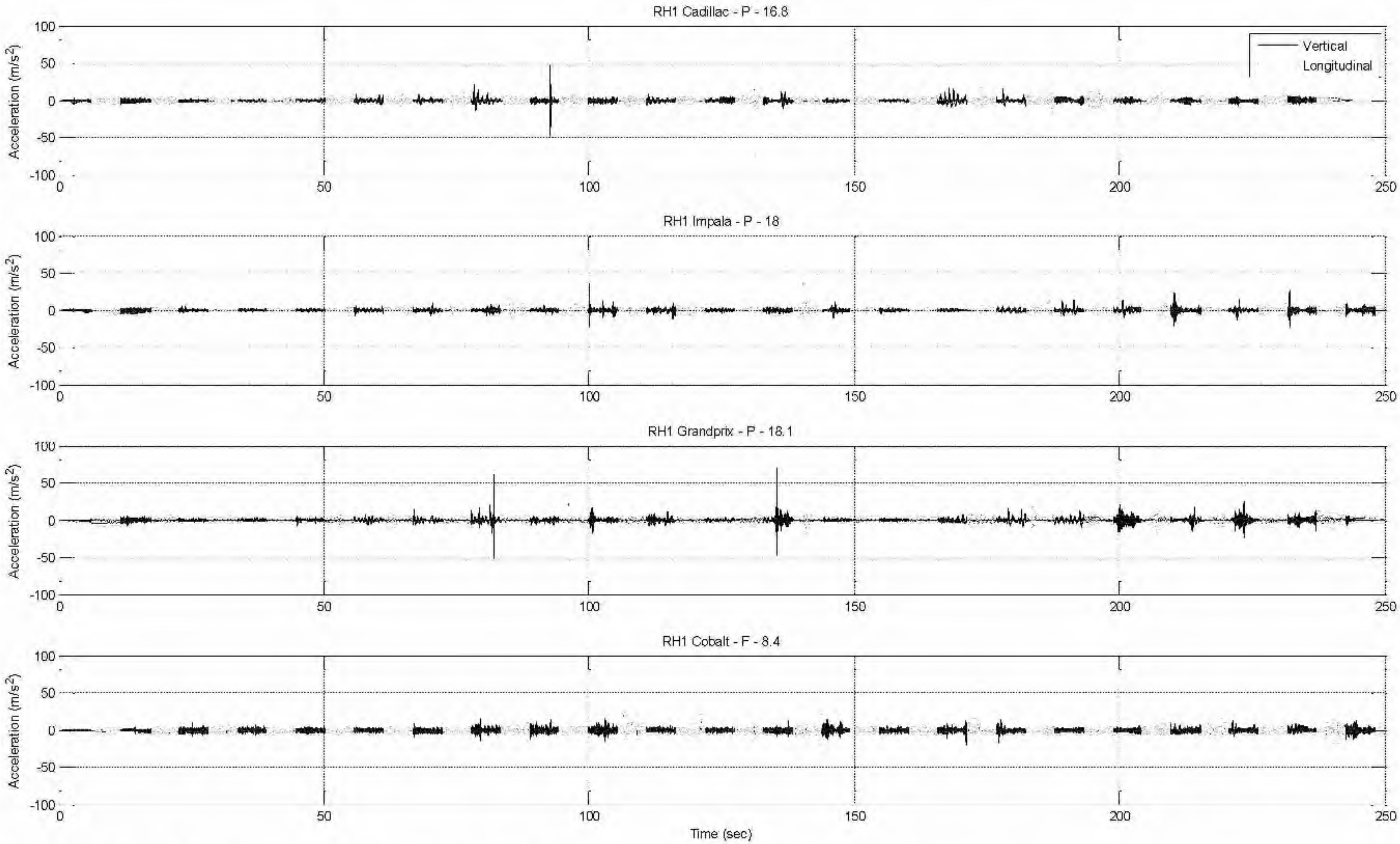


Figure 32. Vertical and longitudinal accelerations of Ride and Handling Loop #1 test.

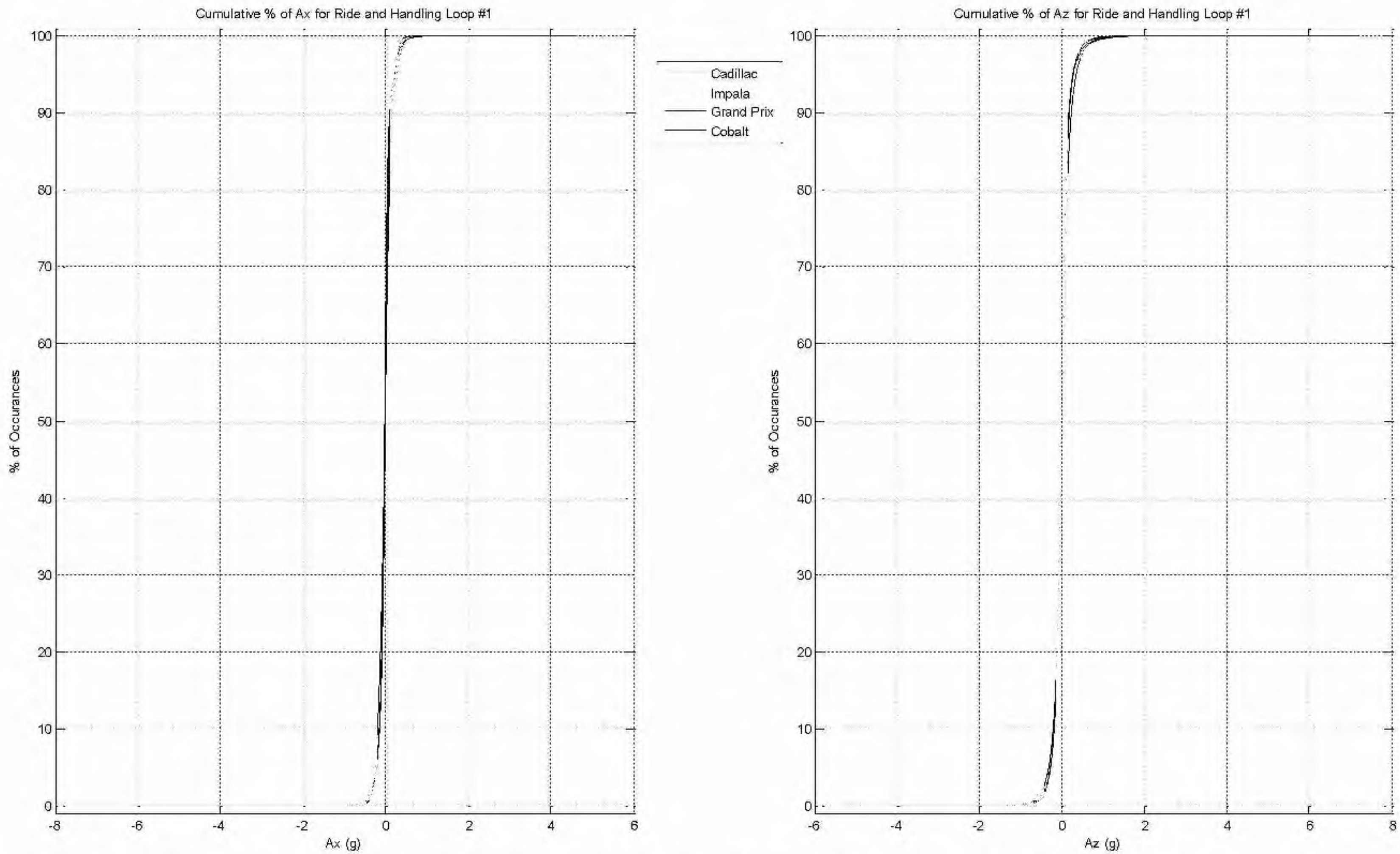


Figure 33. Cumulative percentage of vertical and longitudinal accelerations for Ride and Handling Loop #1 test.

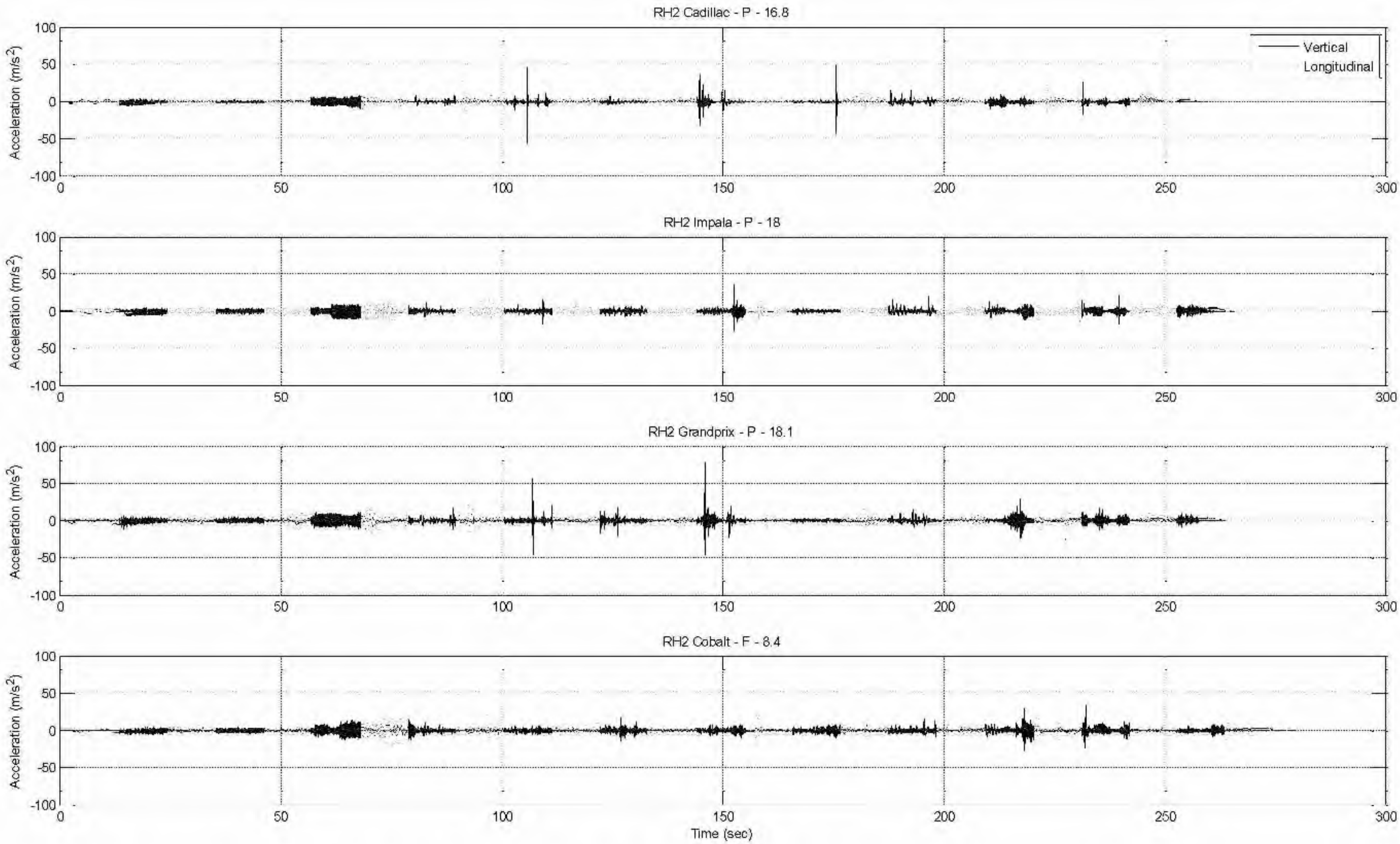


Figure 34. Vertical and longitudinal accelerations of Ride and Handling Loop #2 test.

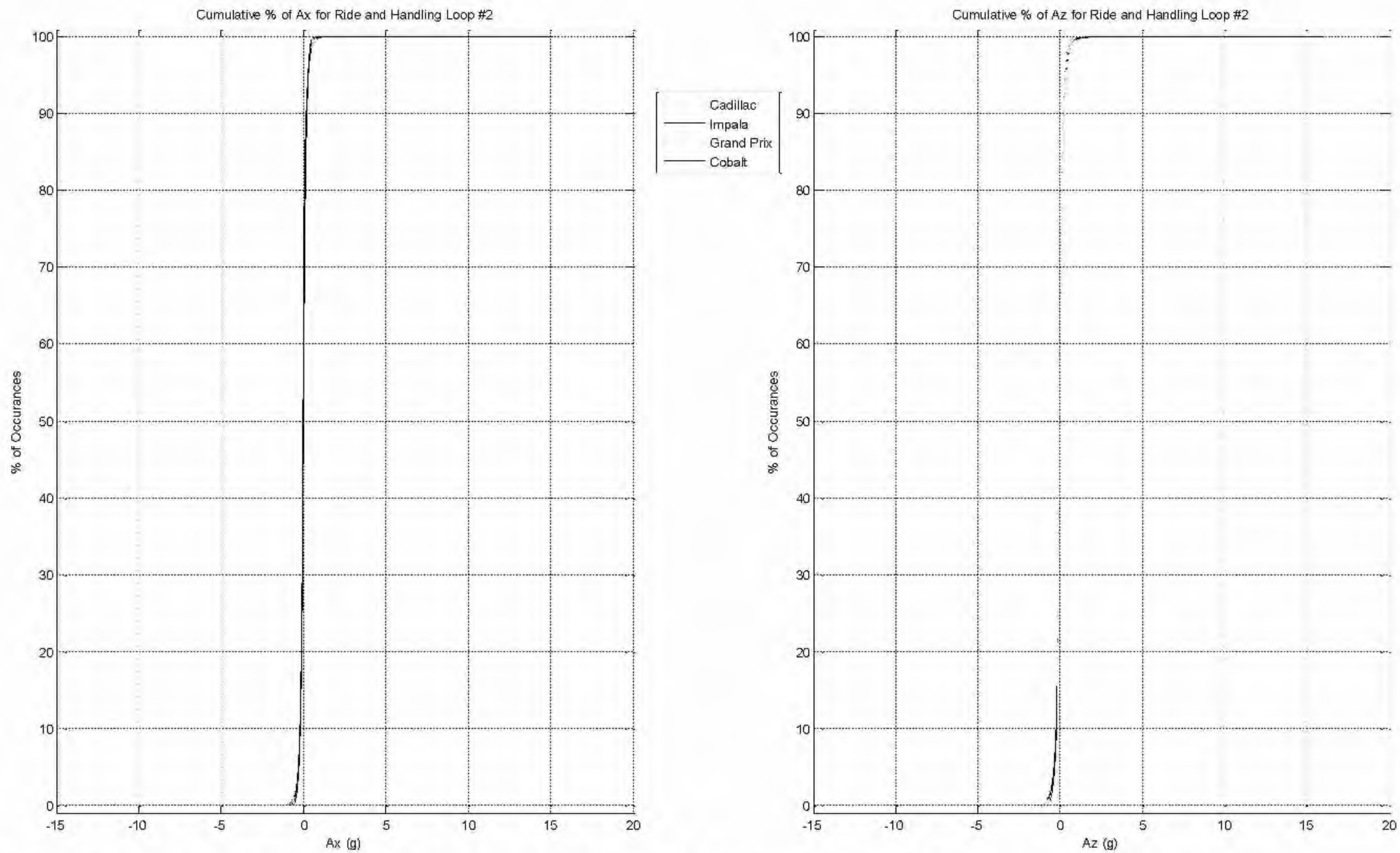


Figure 35. Cumulative percentage of vertical and longitudinal accelerations for Ride and Handling Loop #2 test.

The Cubilete event provides longitudinal and vertical acceleration content (Figure 36) that is similar to the Belgian Block event, though with less magnitude. The cumulative percentage plot for the Cubilete event is illustrated in Figure 37.

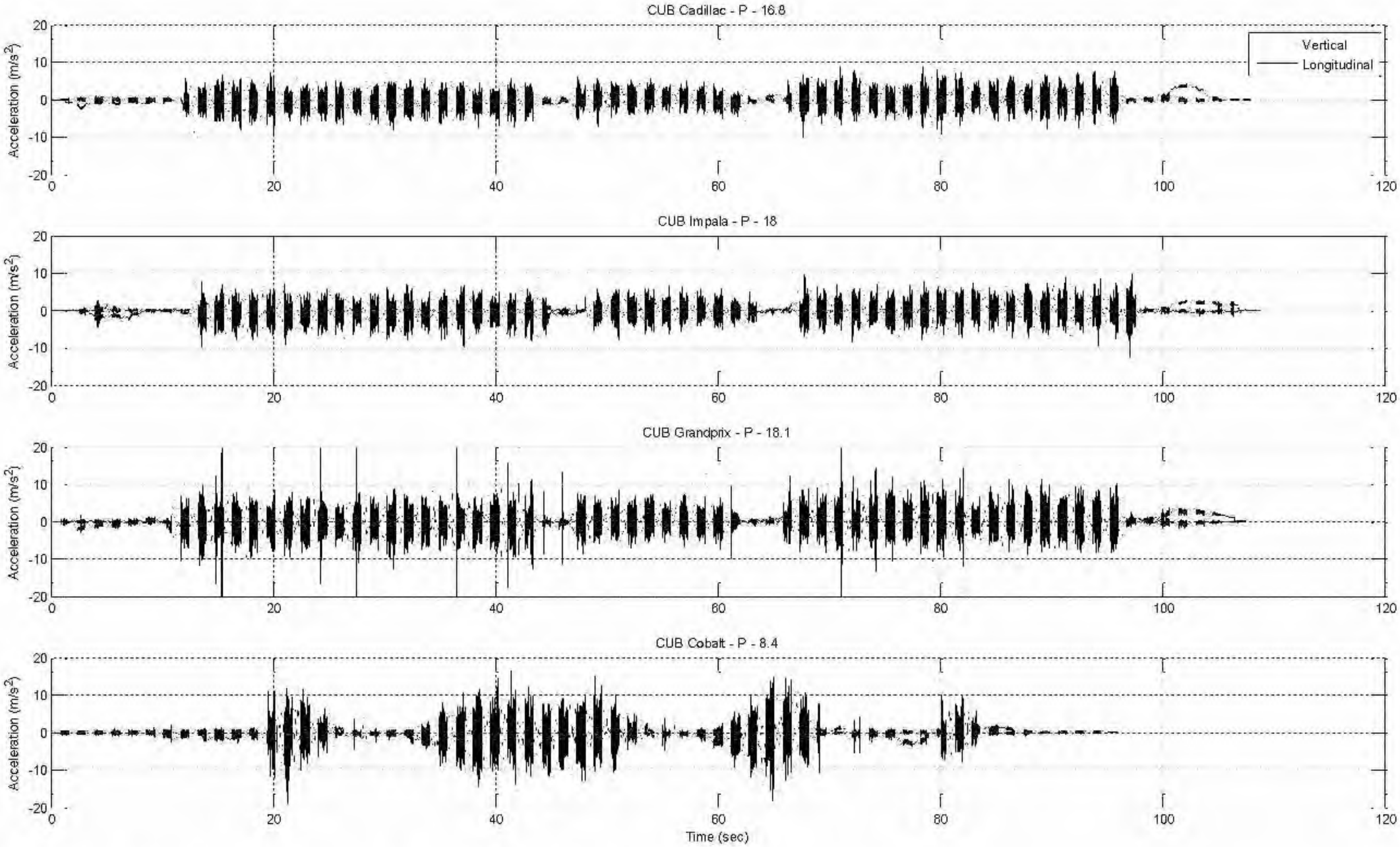


Figure 36. Vertical and longitudinal accelerations of Cubilete test.

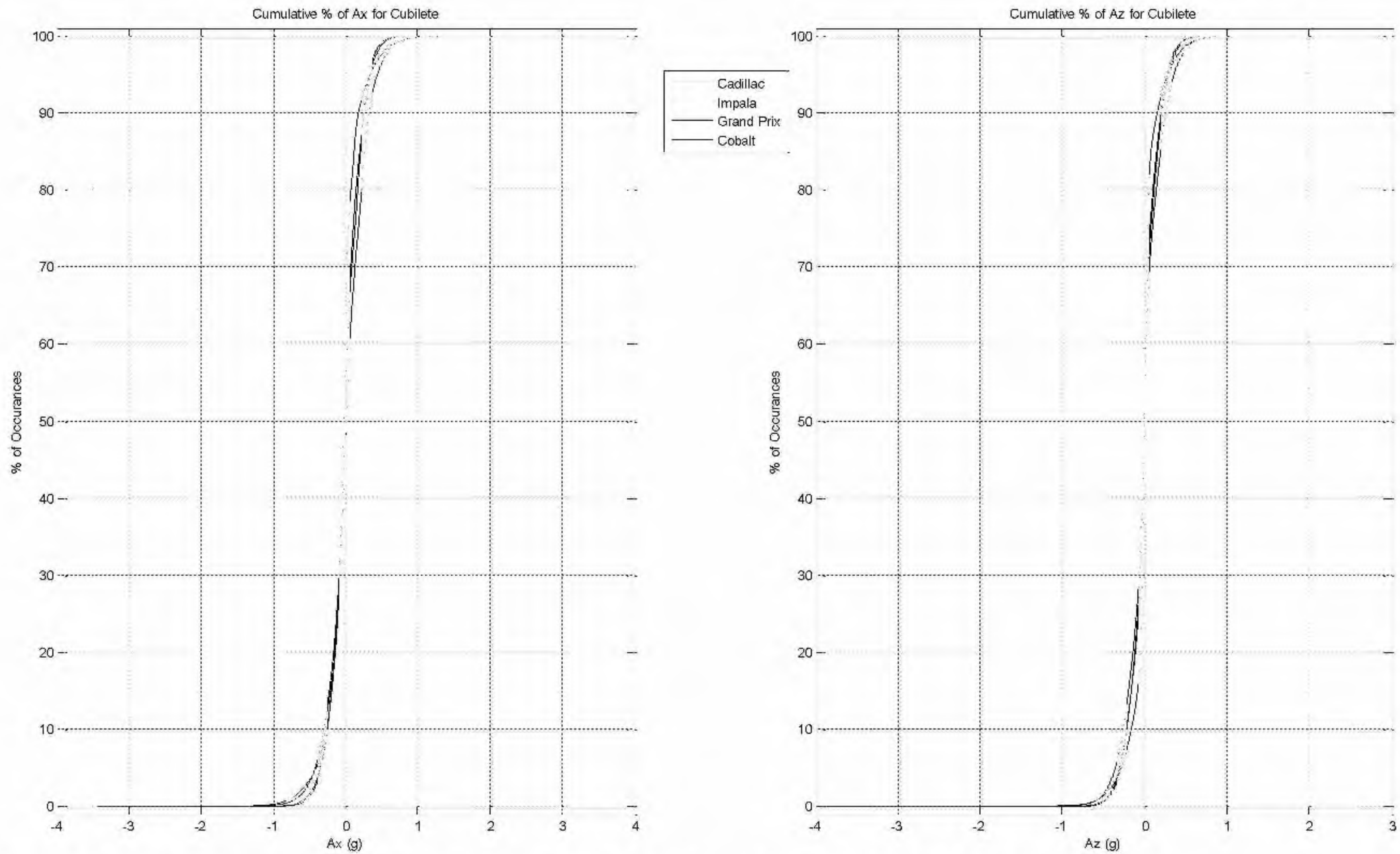


Figure 37. Cumulative percentage of vertical and longitudinal accelerations for Cubilete test.

The Panic Stop event produces a large spike in longitudinal acceleration during braking, as shown in the time-history data (Figure 38). The cumulative percentage (Figure 39) verifies this result, thus indicating a difference in the 50-99 percent portion of the data that correlates to the longitudinal acceleration in the braking direction.

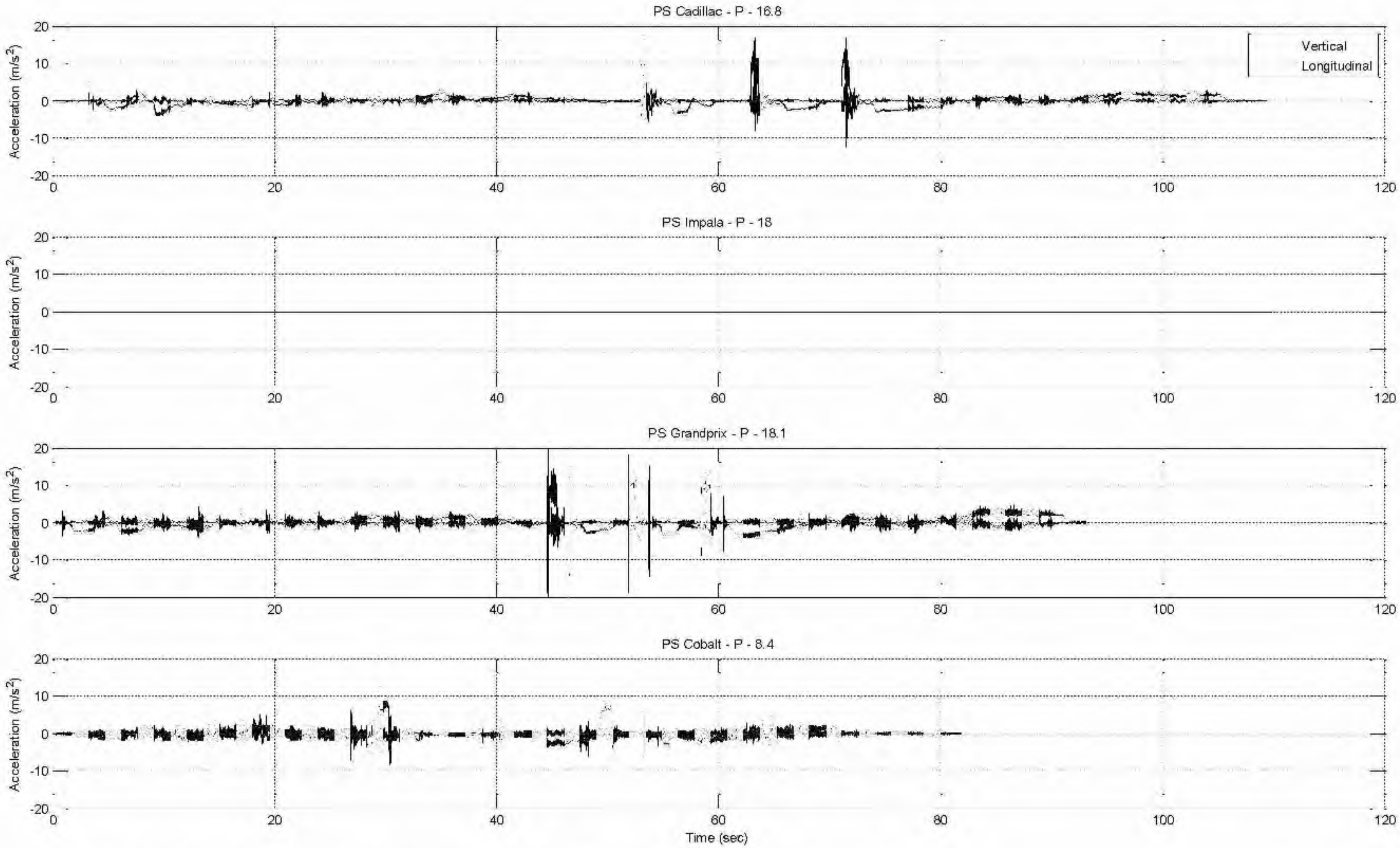


Figure 38. Vertical and longitudinal accelerations of Panic Stop test.

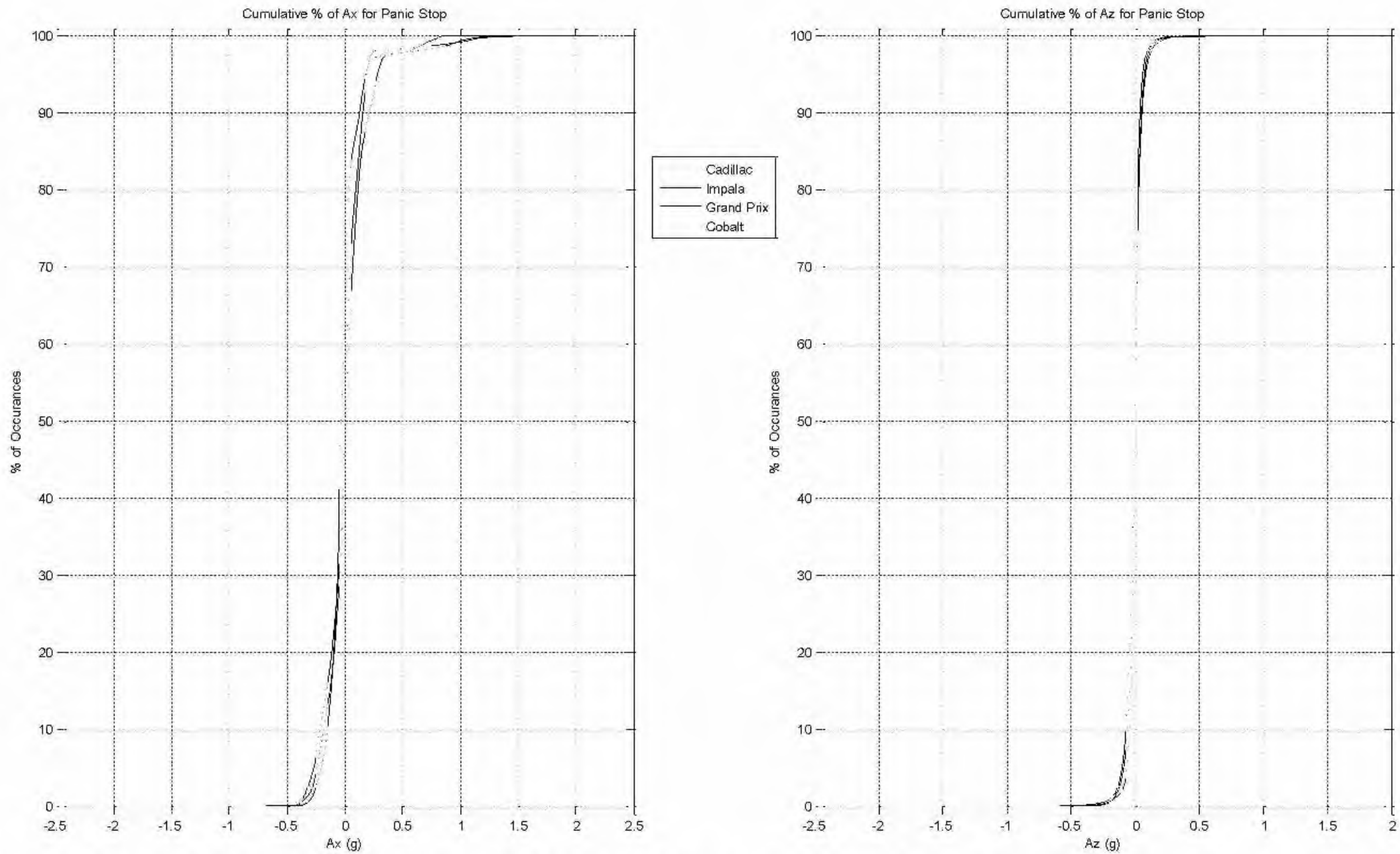


Figure 39. Cumulative percentage of vertical and longitudinal accelerations for Panic Stop test.

When performing the GM MPG inertial test using the 0.7 lb key mass, if the vehicle does not experience an unintended key rotation, the vehicle is graded as a pass (as illustrated in Table 5) and the next vehicle is then tested. However, the VTTI project team recommends that each sample vehicle run across the GM MPG events be tested multiple times before moving to the next vehicle to ensure that statistical confidence is gained in the results of the inertial test (i.e., that the vehicle passes the events multiple times at the heaviest key mass).

Subtask 2: Predictive Model

The resulting time-history data presented during Subtask 1 are used herein to correlate and validate a predictive model for unintended ignition key rotation.

A predictive model of the ignition switch can be developed by using a pendulum attached to the key that represents the key ring and the contents of the key chain. This predictive model is shown in Figure 40.

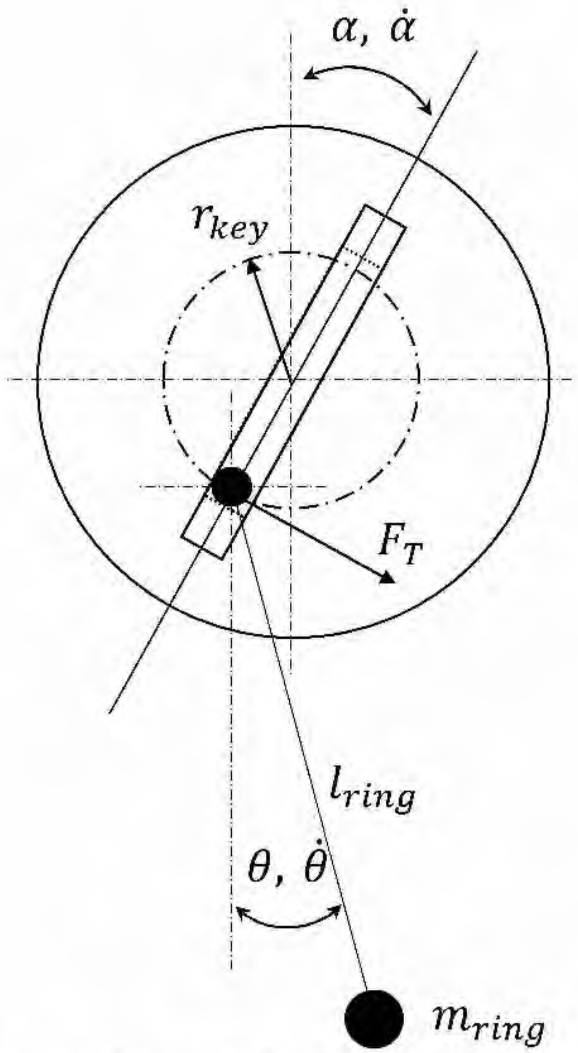


Figure 40. Model of ignition/key interface with key ring and mass hanging from the key.

The mass of the contents hanging from the key chain is represented by the m_ring parameter; the l_ring parameter approximates the key ring diameter and is the distance from the key to the center of the mass of contents hanging from the key ring. The α parameter is the angle of the key head in "Run" position, and the θ parameter is the angle of the pendulum relative to the vertical direction of the vehicle.

The r_key parameter is the distance from the center of the key to the location where the key ring hangs from the ignition key. If the ignition key has a slot design, the r_key parameter is the distance from the center of the ignition key to the edge of the slot. Finally, the F_T parameter is the inertial force acting on the ignition key trying to move the key from the "Run" to "Accessory" position. Note that this model can be applied to both column- and steering wheel-mounted ignition switches.

The predictive dynamic model is developed in Appendix C, but the significant properties of that model will be provided below.

The inertial acceleration experienced by the vehicle will act on m_{ring} and will produce a force F_T and torque that will try to move the ignition state from "Run" to "Accessory." By design, the ignition system requires the torque applied to the ignition key to exceed some threshold value before the key rotates. If $Torque_{key}$ is the torque acting on the ignition key due to inertial accelerations experienced by the vehicle and $Torque_{Threshold}$ is the torque required to move the ignition key from "Run" to "Accessory," then inadvertent ignition key rotation due to inertial accelerations will occur when the following equation is true:

$$Torque_{key} > Torque_{Threshold}$$

Using the derivation of the predictive model in Figure 40, $Torque_{key}$ is

$$Torque_{key} = r_{key} \cdot F_{T,key}$$

Or

$$Torque_{key} = r_{key} \cdot m_{ring} \cdot \left[(a_z + g) \cdot \cos\theta \cdot \sin\gamma + a_x \cdot \sin\theta \cdot \sin\gamma + \dot{\theta}^2 \cdot l_{ring} \cdot \sin\gamma\right]$$

It should be noted that, based on the equation of $Torque_{key}$, as $r_{key} \to 0$, the torque applied to the ignition key moves to zero if the key ring does not bind, or become locked up on the key head (see Subtask 5 for more information about key binding). This implies that, as the length of the slot in the ignition key head design becomes smaller (i.e., becomes a hole), the torque acting on the ignition switch due to inertial accelerations goes to zero, and the potential for inadvertent key rotation is minimized. One caveat to this is that, if the key ring binds on the head of the ignition key, it does not matter if the key has a hole or slot design because the point at which the ring binds on the key head will produce a torque that will act to rotate the ignition key.

The second item of note is that, if $r_{key} \neq 0$, then the torque applied to the ignition key is a function of the inertial accelerations applied to the pendulum mass, the angular velocity of the pendulum swing, and the angle of the pendulum relative to the ignition key. The effect of each inertial component is then a function of the angle of the pendulum relative to the ignition key, the accelerations applied to the pendulum mass, and how fast the pendulum is swinging. Therefore, the actual inertial effect is a combination of all inertial accelerations acting on the vehicle and how the key chain contents are swinging on the key chain.

The dynamic equations describing the pendulum model can be implemented into a math computational and visualization program known as MATLAB, and inertial input time histories can be simulated. The resulting inertial key torque can then be calculated. Figure 41 depicts the pendulum model implemented in MATLAB.

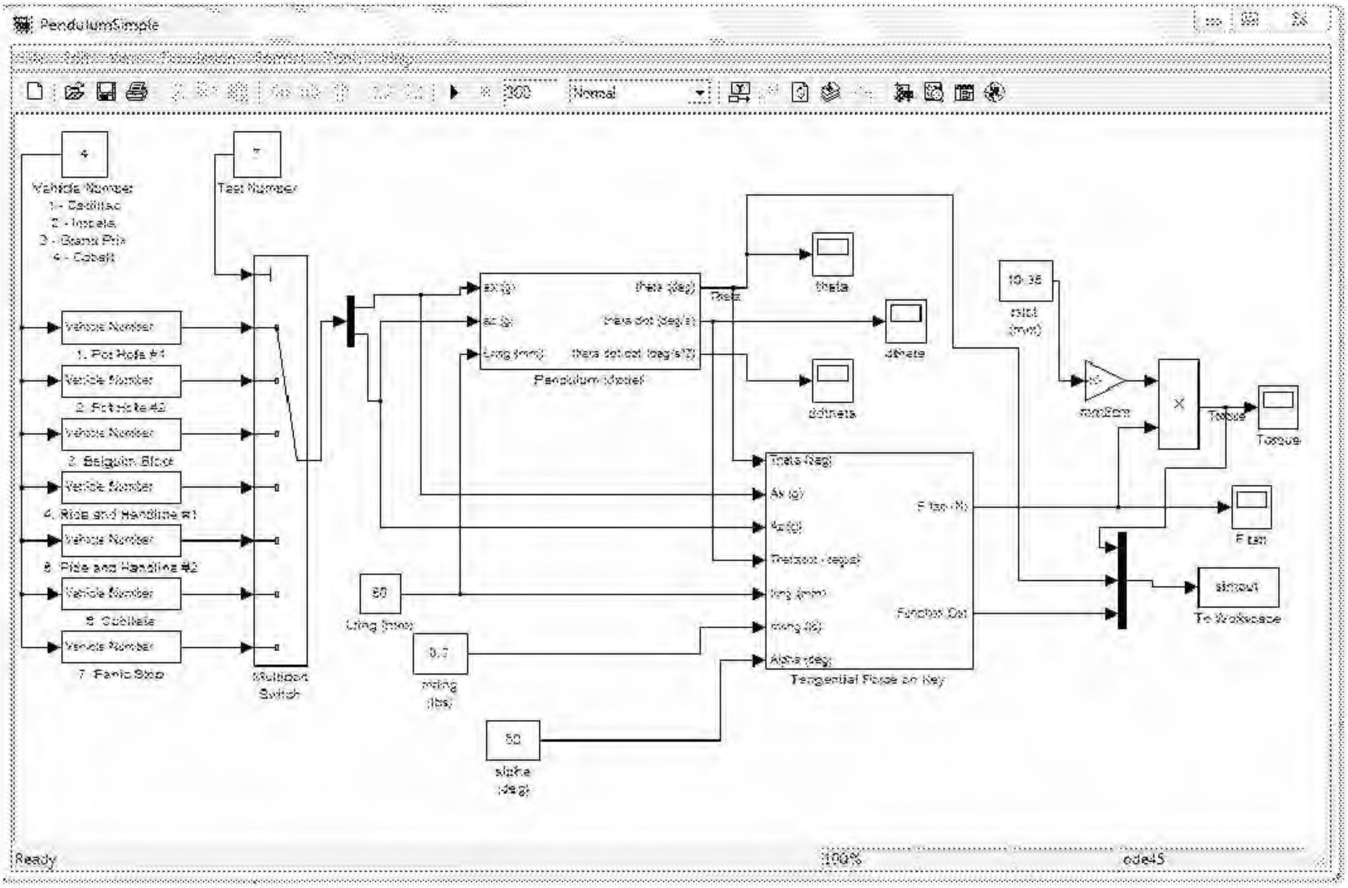


Figure 41. MATLAB Simulink Model of the pendulum.

Note that the predictive model is expressed using the parameters m_{ring}, l_{ring}, and α. As inputs, the model uses the steering column accelerations available from the GM MPG test data that were provided to the VTTI project team.

Simulations of the predictive model developed by the VTTI project team were performed to understand its applicability and validity. The acceleration time-history input was simulated, and the resulting inertial key torque response was compared to the static-measured torque of the four sample vehicles described during Subtask 1 (i.e., 2007 Cadillac DTS, 2007 Chevrolet Impala, 2008 Pontiac Grand Prix, and 2005 Chevrolet Cobalt). The points during which the inertial key torque response exceeded the static-measured torque were then compared to the pass/fail criteria presented in Table 5. As seen in the table, Potholes #1 and #2 and Ride and Handling Loops #1 and #2 caused some of the sample vehicles to experience an inadvertent ignition key rotation. Therefore, it can be determined that such GM MPG events are important when evaluating the validity of the predictive model.

Figure 42 through Figure 50 are inertial key torque results from the predictive model simulation. Each figure has four time-history plots, where each plot represents one of the four sample vehicles tested (e.g., Cadillac, Impala, Grand Prix, and Cobalt). Each

plot has a solid black line that represents the measured system-level static torque required to move the ignition key from "Run" to "Accessory" (i.e., the threshold torque). If the predictive model was validated, then any inertial key torque exceeding the black line would cause an unintended ignition key rotation.

Figure 42 through Figure 50 illustrate that the predictive model does a reasonable job predicting unintended ignition key rotation, but there are some false-positive events. False-positive events are points during the time history when the predicted key torque exceeds the threshold torque value but a change in the ignition state did not occur during the GM MPG inertial events. Such false-positives could be caused by using the static torque as the threshold torque during instances when the dynamic torque of the ignition switch may be greater than the static torque. Furthermore, the time duration during which the inertial key torque exceeds the static torque may result in a false-positive because, to inadvertently rotate the ignition key, the inertial key torque may have to exceed the static torque for a prescribed time so that the ignition key can start to move out of the "Run" position. Finally, the predictive model is a simple model, so the false-positives may be caused by the fact that the predictive model requires refinement. However, even in light of the false-positives, the predictive model does a reasonable job predicting unintended key rotation and can be used in the future to understand any unintended ignition key rotation issues in GM vehicles.

Figure 42 and Figure 43 illustrate the inertial key torque simulations from the Belgian Block data. As shown in Table 5, all vehicles passed this GM MPG event, which means that no inadvertent ignition key rotation occurred. Note in Figure 42 that all of the vehicles except the 2005 Chevrolet Cobalt show inertial key torques lower than their static threshold values. However, the Cobalt shows four instances during which the key torque exceeds the static threshold value. To further investigate this finding, Figure 43 shows a magnified view of two Cobalt instances during which a key torque exceeded a static threshold value at the end of the time history. What can be seen in Figure 43 is that the key torque only exceeds the threshold torque by approximately 15 percent for a short period of time, thus producing a false-positive reading.

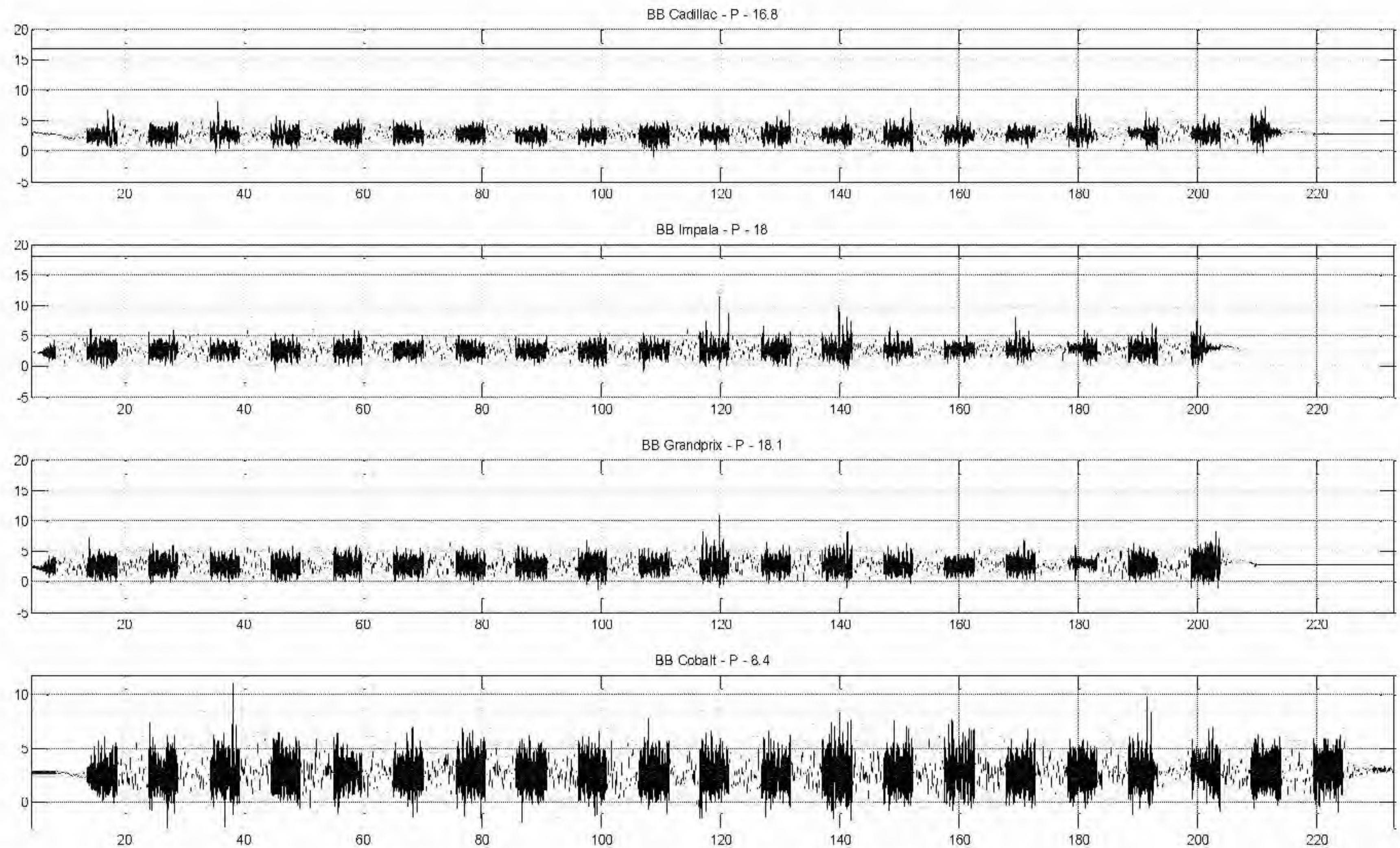


Figure 42. Model simulation of inertial key torque response on Belgian Block test.

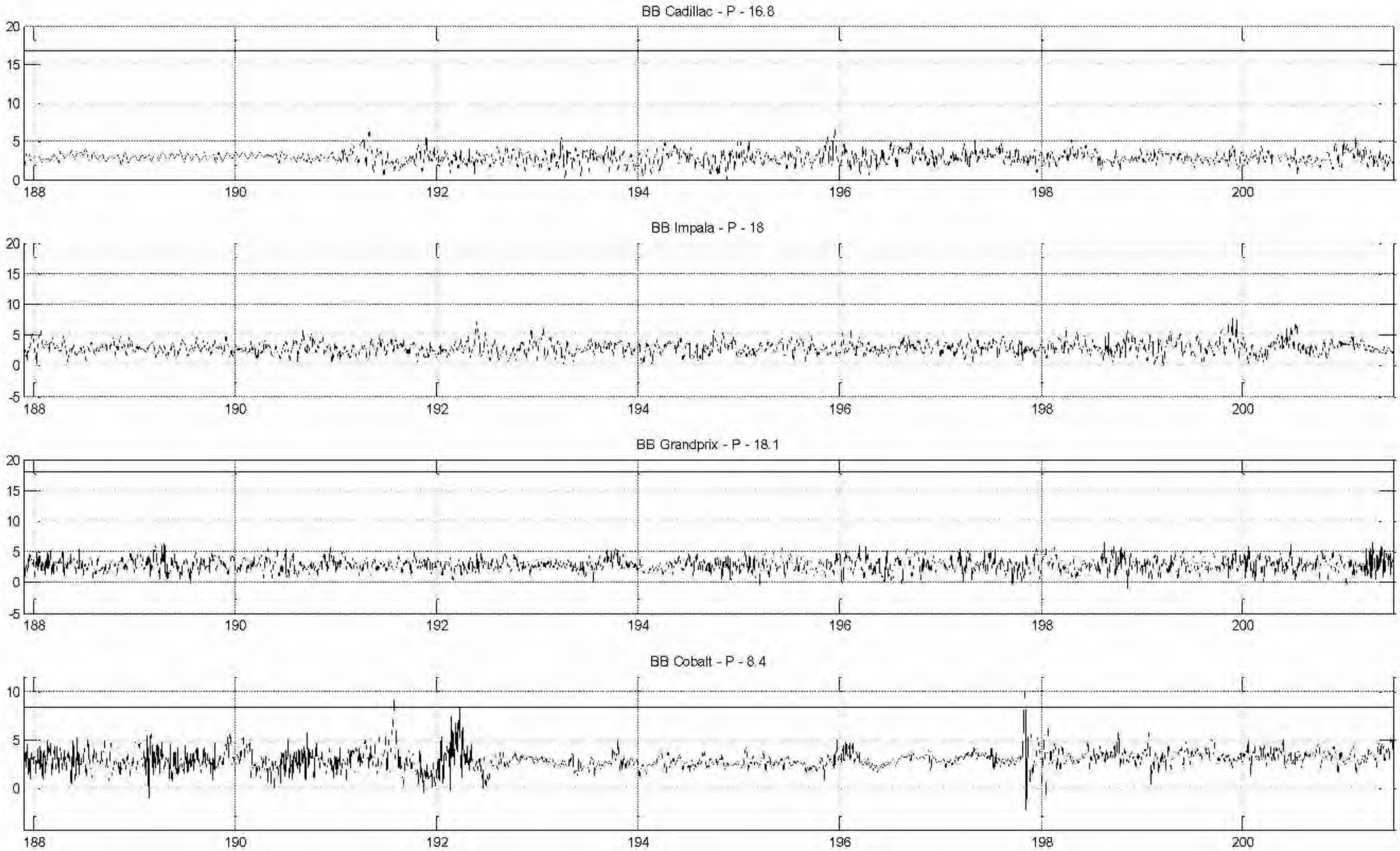


Figure 43. Detail of 2005 Chevrolet Cobalt false-positive in the model simulation of inertial key torque response on Belgian Block test.

Figure 44 through Figure 46 illustrate the inertial key torque simulations for the Ride and Handling Loop #2 event. Of all four GM vehicles field tested, the only vehicle that experienced an unintended ignition key rotation during this event was the 2005 Chevrolet Cobalt (two shutoff events were reported for the Cobalt by GM during the Ride and Handling Loop #2). Figure 44 shows two instances from the model simulation during which the Cobalt experienced an unintended ignition key rotation on this GM MPG event. However, the same figure also shows three false-positives for the 2008 Pontiac Grand Prix and one false-positive for the 2007 Chevrolet Impala. To further investigate these false-positive events versus the Cobalt positive event, Figure 45 and Figure 46 show two magnified plots of the false-positives. Figure 45 shows the Impala false-positive and one Cobalt positive. Note how the time duration of the Impala exceeding its threshold torque is much lower than the time duration of the Cobalt exceeding its threshold torque. Figure 46 shows a Grand Prix false-positive and the Cobalt positive. Note that the Grand Prix data have a short duration during which the threshold torque was exceeded; it appears that the input data may be suspect at this point.

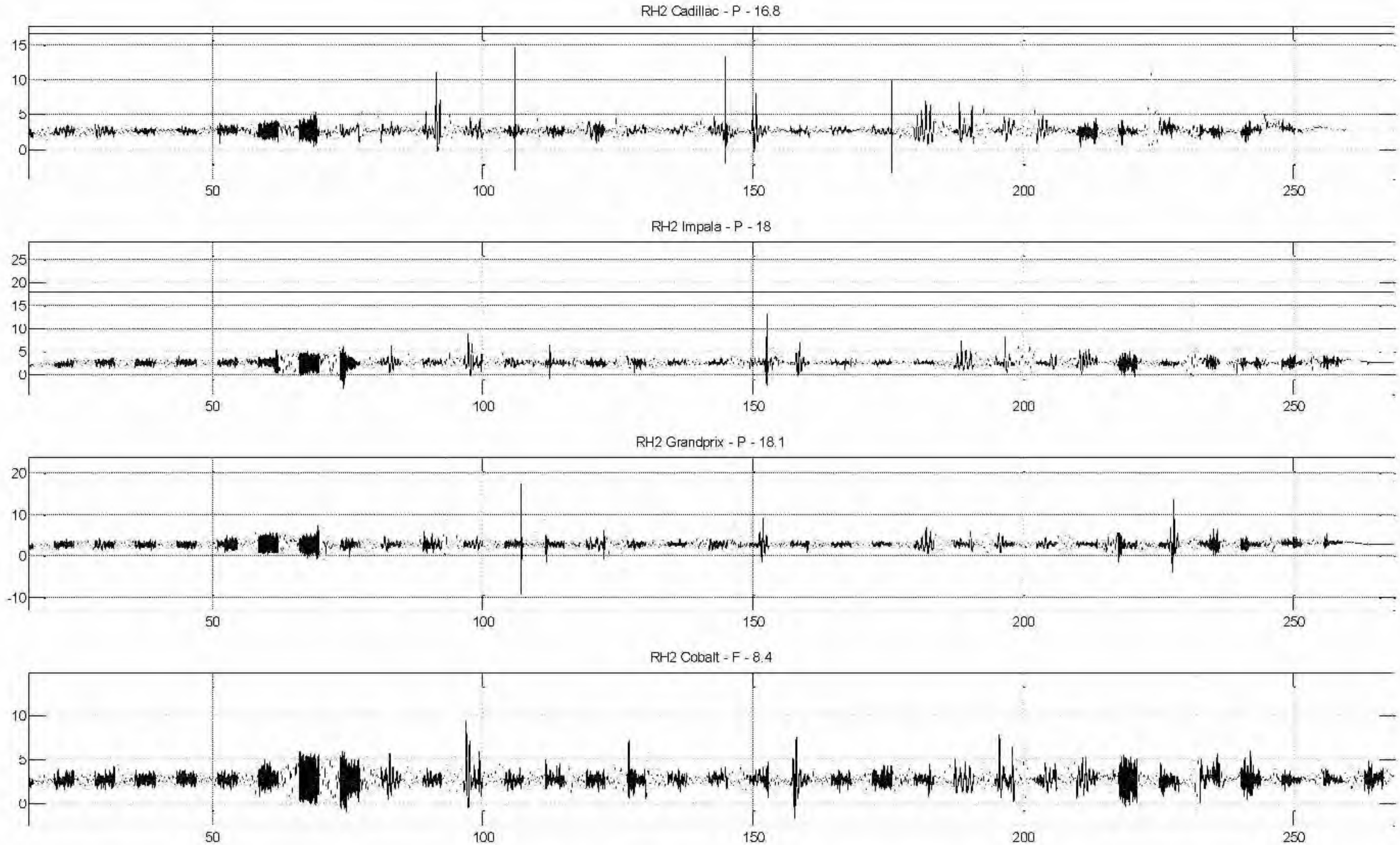


Figure 44. Model simulation results of Ride and Handling Loop #2 test.

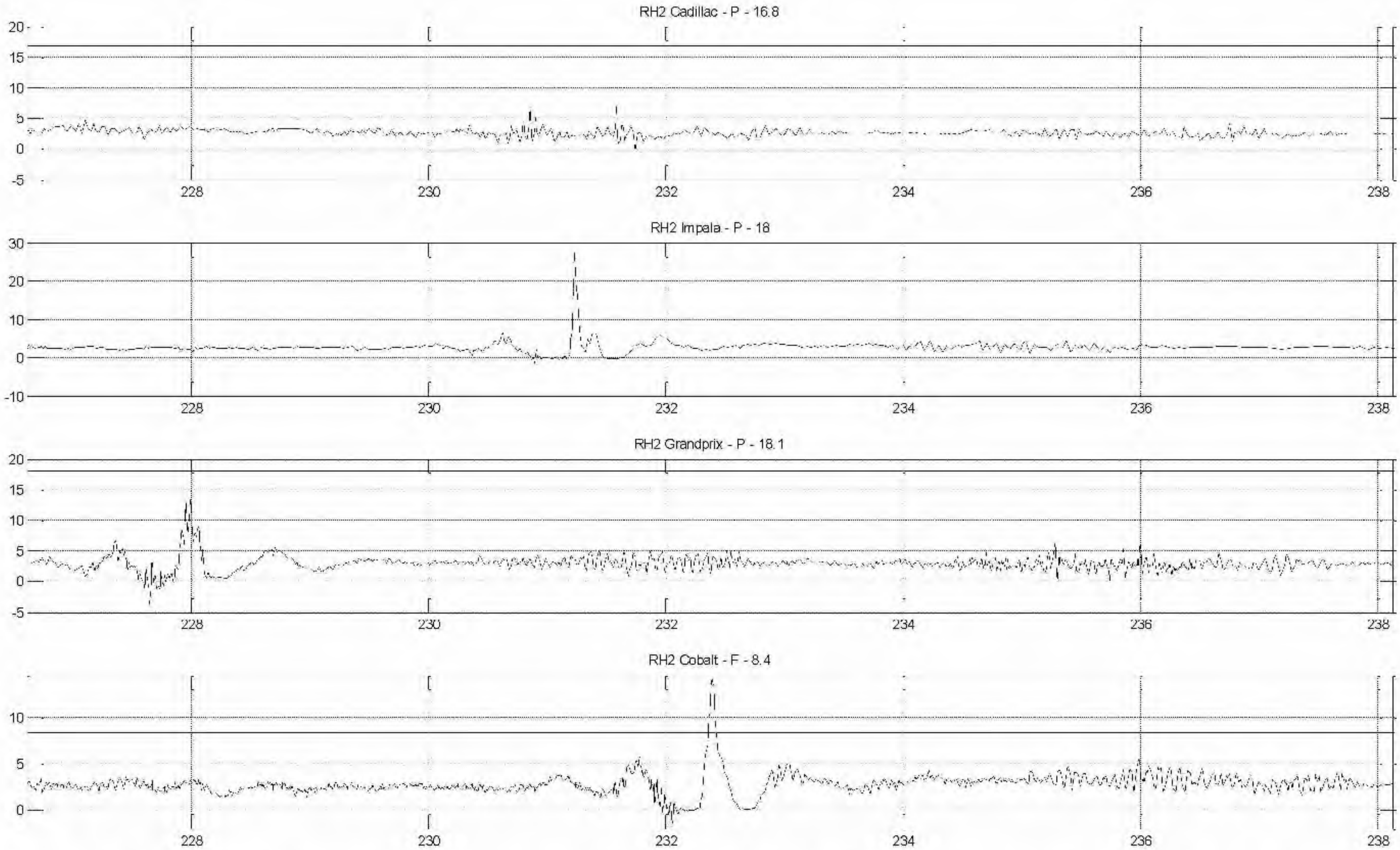


Figure 45. Detail of 2007 Chevrolet Impala false-positive vs. 2005 Chevrolet Cobalt positive in model simulation results of Ride and Handling Loop #2 test.

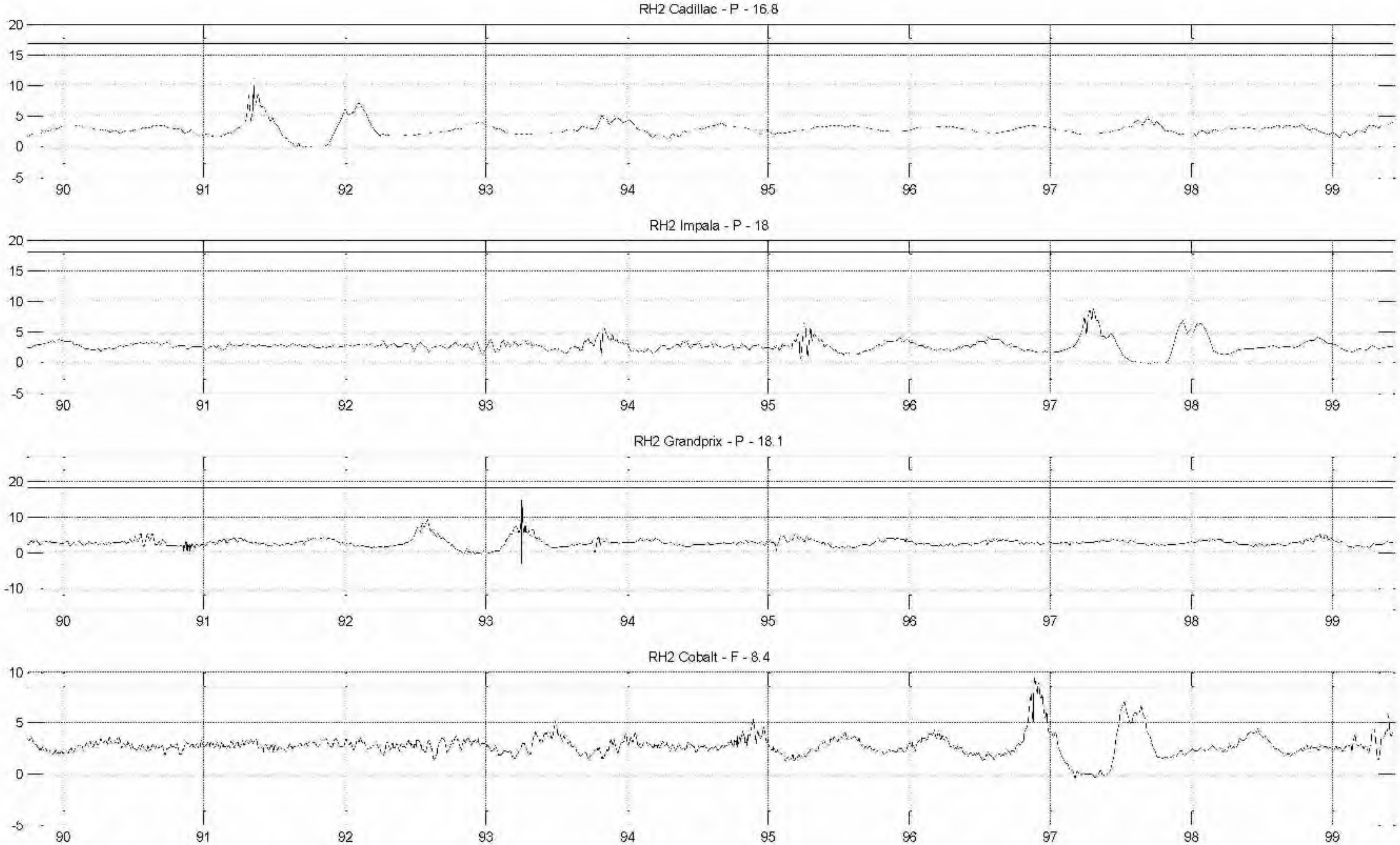


Figure 46. Detail of 2008 Pontiac Grand Prix false-positive vs. 2005 Chevrolet Cobalt positive in model simulation results of Ride and Handling Loop #2 test.

Figure 47 and Figure 48 illustrate the inertial key torque simulation results for the Pothole #1 event. As seen in Table 5, the 2007 Chevrolet Impala and the 2005 Chevrolet Cobalt experienced unintended ignition key rotations during this GM MPG event. Figure 47 shows that all four vehicles produced inertial key torques that exceeded their threshold torques. Figure 48 is a magnified plot of the 2007 Cadillac DTS and Impala, allowing a comparison to be made between the Cadillac false-positive and the Impala positive. Figure 48 clearly shows the model predicted that the Cadillac exceeded its threshold torque by less than 10 percent for a short period of time, whereas the Impala exceeded its threshold torque for a sustained period of time.

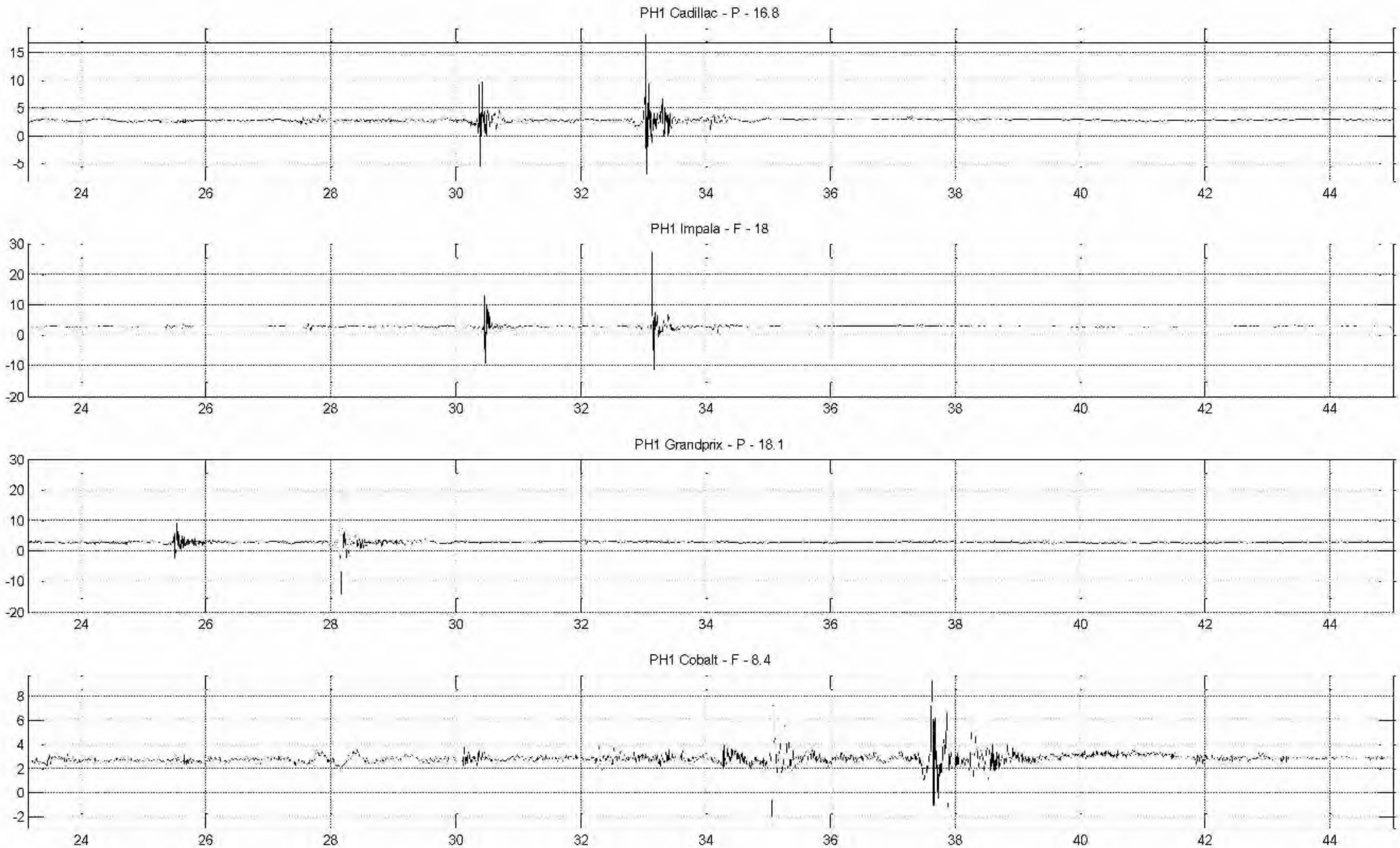


Figure 47. Model simulation results of Pothole #1 test.

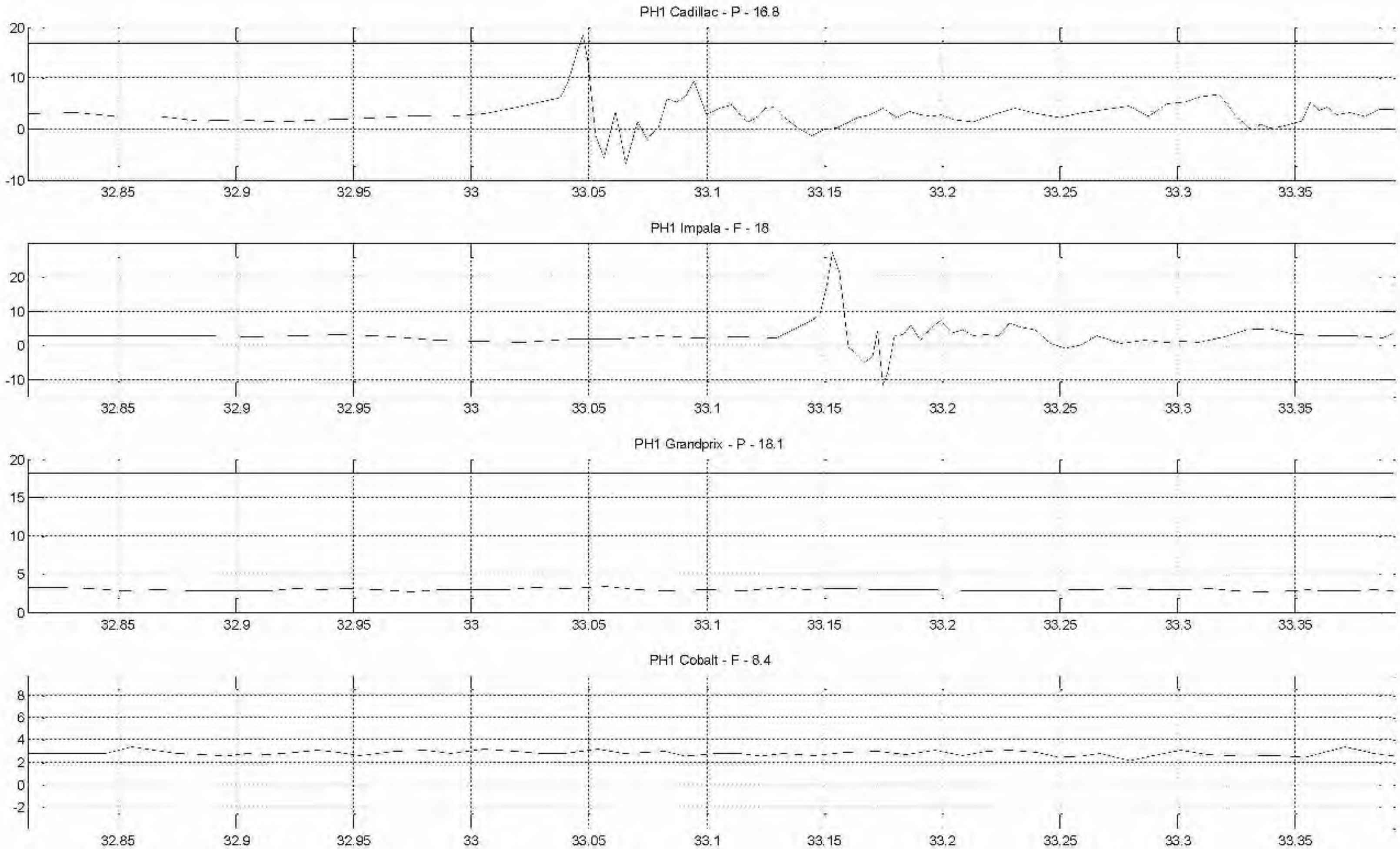


Figure 48. Detail of 2007 Cadillac DTS false-positive vs. 2007 Chevrolet Impala positive in model simulation results of Pothole #1 test.

Figure 49 and Figure 50 show the inertial key torque simulations for the Pothole #2 event. As seen in Table 5, the 2007 Cadillac DTS, 2007 Chevrolet Impala, and 2005 Chevrolet Cobalt all experienced unintended key rotations during this GM MPG event. Figure 49 predicts that all four vehicles will experience unintended key rotations on the Pothole #2 event. Figure 50 is a magnified view of the points during which the threshold torque was exceeded for the Cadillac, Impala, and the 2008 Pontiac Grand Prix. The Grand Prix results are indicative of a false-positive that may be due to model refinement. That is, the duration of the Grand Prix exceeding its threshold torque is shorter than that of the Cadillac and Impala but not sufficiently different.

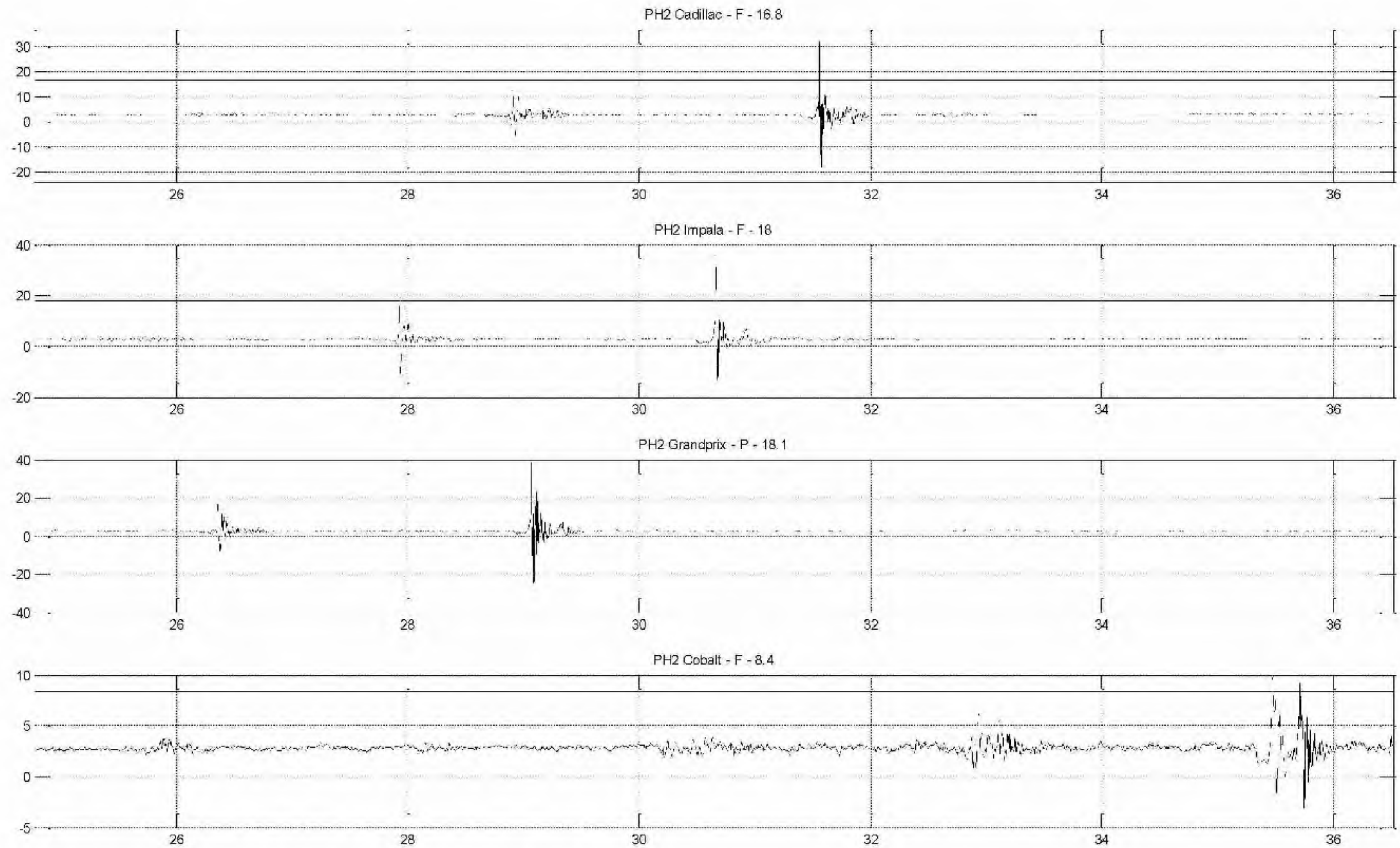


Figure 49. Model simulation results of Pothole #2 test.

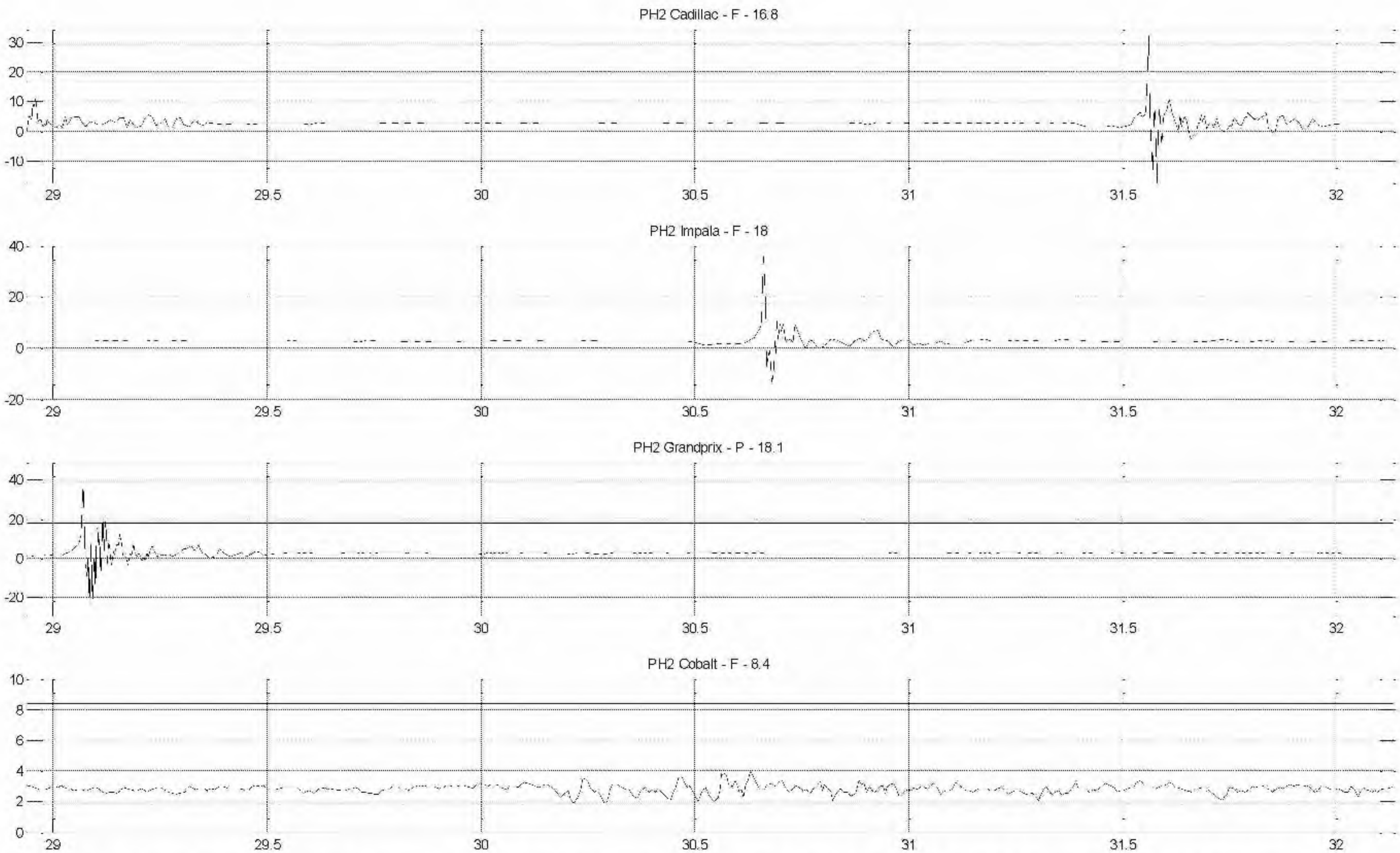


Figure 50. Detail of 2008 Pontiac Grand Prix false-positive vs. 2007 Cadillac DTS and 2007 Chevrolet Impala positives in model simulation results of Pothole #2 test.

In conclusion, when the vehicle-level static torque was used as the threshold value to predict an unintended key rotation, the predictive model developed by the VTTI project team predicted all of the ignition deactivation events experienced during physical testing of the four sample vehicles on the GM MPG. This predictive model included false-positives, but the duration of the key torque exceeding the threshold torque was less than the durations seen for the true positive results. Even though the predictive model may need some refinement, it is a reasonable start in capturing and predicting ignition deactivation events due to inertial effects and can be used to physically describe the inertial phenomenon experienced at the ignition key.

Subtask 3: Dynamic In-vehicle Measurements

During this subtask, VTTI engineers traveled to the GM MPG and installed the institute's DAS units in three GM vehicles and three non-GM vehicles. These six vehicles were chosen to represent a range of vehicle chassis and vehicle body responses to inertial effects produced by the eight GM MPG events. The selected vehicles varied in class, from small compact vehicles to vehicles with sport-style suspensions to a large SUV. The data taken with the VTTI DAS comprised measurements recorded using low- and high-speed settings. The low-speed setting recorded measurements at 10 samples per second (i.e., 10 Hz), which is the standard frequency used to record data points in the SHRP 2 NDS while the ignition switch is in the "Run" position; the high-speed setting recorded the data at 640 samples per second (i.e., 640 Hz) for a duration of 15 seconds. The high-speed recordings were triggered manually by VTTI engineers to capture higher frequency segments across the eight GM MPG events.

The purpose of these measurements made using the VTTI DAS was to create a data set that could be directly compared to the naturalistic driving data found in the SHRP 2 NDS database. Such a comparison facilitates an understanding of how the GM MPG events compare to real-world driving events found in the SHRP 2 NDS database. That is, if the GM MPG events were found to exceed driving levels in the SHRP 2 NDS database, then use of the MPG events in determining inertial effects on unintended ignition key rotation could be validated.

In terms of capturing peak acceleration, the sample rate of 10 Hz is too low to detail the actual acceleration experienced by the vehicles in the SHRP 2 NDS database. However, as the amount of data samples are increased, the fidelity of the acceleration content seen by the vehicles improves. Thus, performing a statistical analysis on a large data set provides insight into what levels of acceleration are seen by the vehicles during normal driving. For this project, more than 1.2 million trips (i.e., key-on to key-off) totaling more than 9 billion data points were used to statistically quantify the acceleration content found in the SHRP 2 NDS data. Figure 51 shows a plot of the frequency of every unique acceleration point versus values for the longitudinal, lateral, and vertical acceleration data, as found in the SHRP 2 NDS database. Note that the magenta dots in the plot indicate the cumulative percentage, or 1-99 percent of data; the remaining data fall within the 0-1 percent and the 99-100 percent cumulative

percentage range. Figure 52 is a magnified plot of the same data, showing the 1-99 percent of the cumulative percentage data.

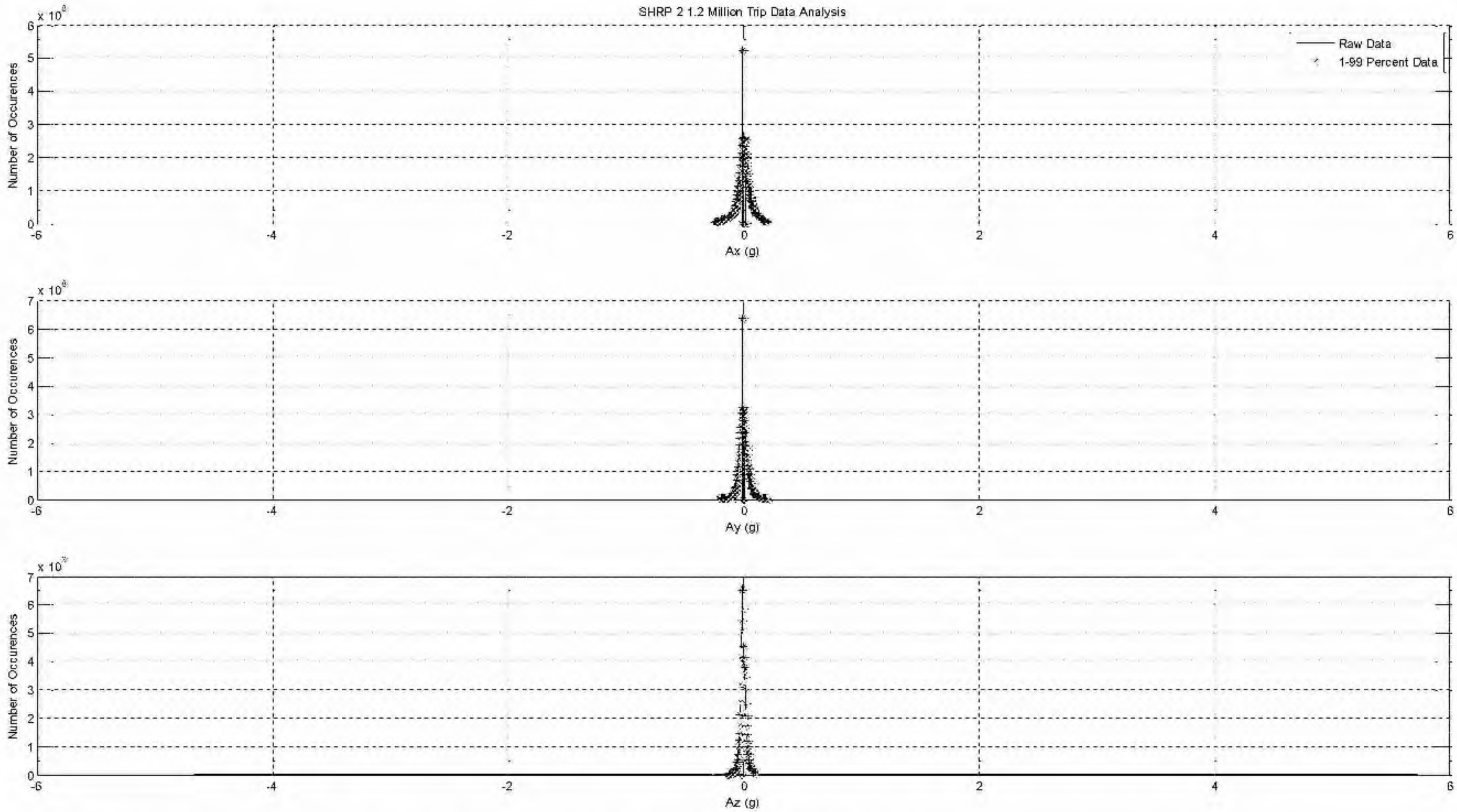


Figure 51. Acceleration value vs. number of occurrences for SHRP 2 NDS data.

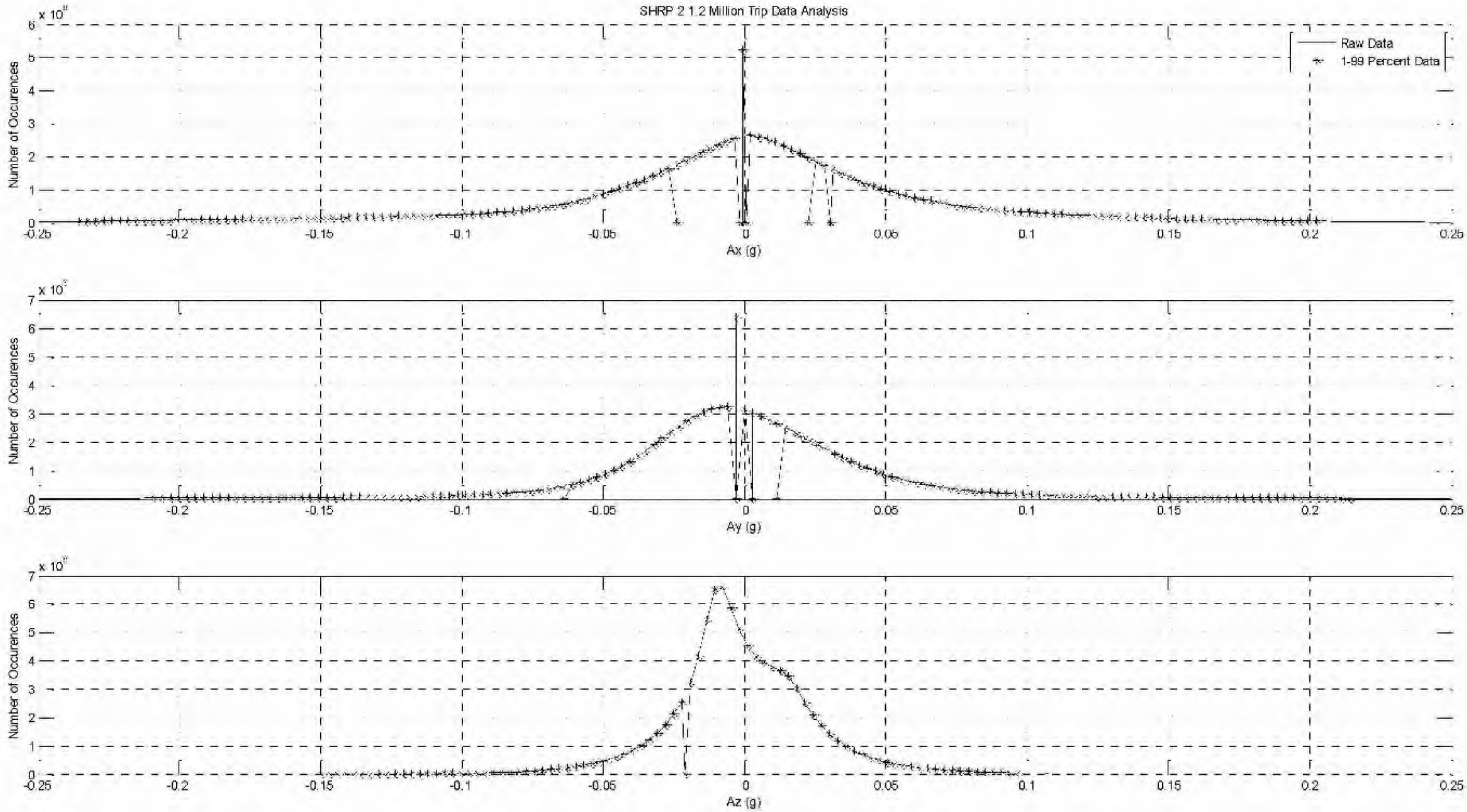


Figure 52. Detailed plot of acceleration value vs. number of occurrences for SHRP 2 NDS data.

Another way to plot the data is to chart the cumulative percentage versus the acceleration value and use it as the reference with which to compare the SHRP 2 data to the GM MPG vehicle data collected by the VTTI DAS.

The in-vehicle data taken at the GM MPG using the VTTI DAS included mounting the DAS in six different vehicles that were then run across the eight inertial events on the GM MPG. The vehicles measured were:

- 2005 Chevrolet Cobalt (two different tests of the same vehicle)
- 2006 Chevrolet Impala
- 2007 GMC Yukon
- 2013 Honda Fit
- 2012 Ford Focus
- 2006 BMW 330ci

The GM MPG events were recorded at the standard 10 Hz sample rate (i.e., low speed) for the trip and at the 640 Hz sample rate (i.e., high speed) for 15-second increments throughout the events. Figure 53 through Figure 56 illustrate the high-speed and low-speed acceleration time-history data recorded with the VTTI DAS. Even though the high-speed data are recorded in 15-second intervals, enough high-speed data were recorded to make the appropriate comparisons between the GM MPG data and the SHRP 2 NDS database. For this analysis, the GM MPG events were lumped according to the figures and then analyzed appropriately.

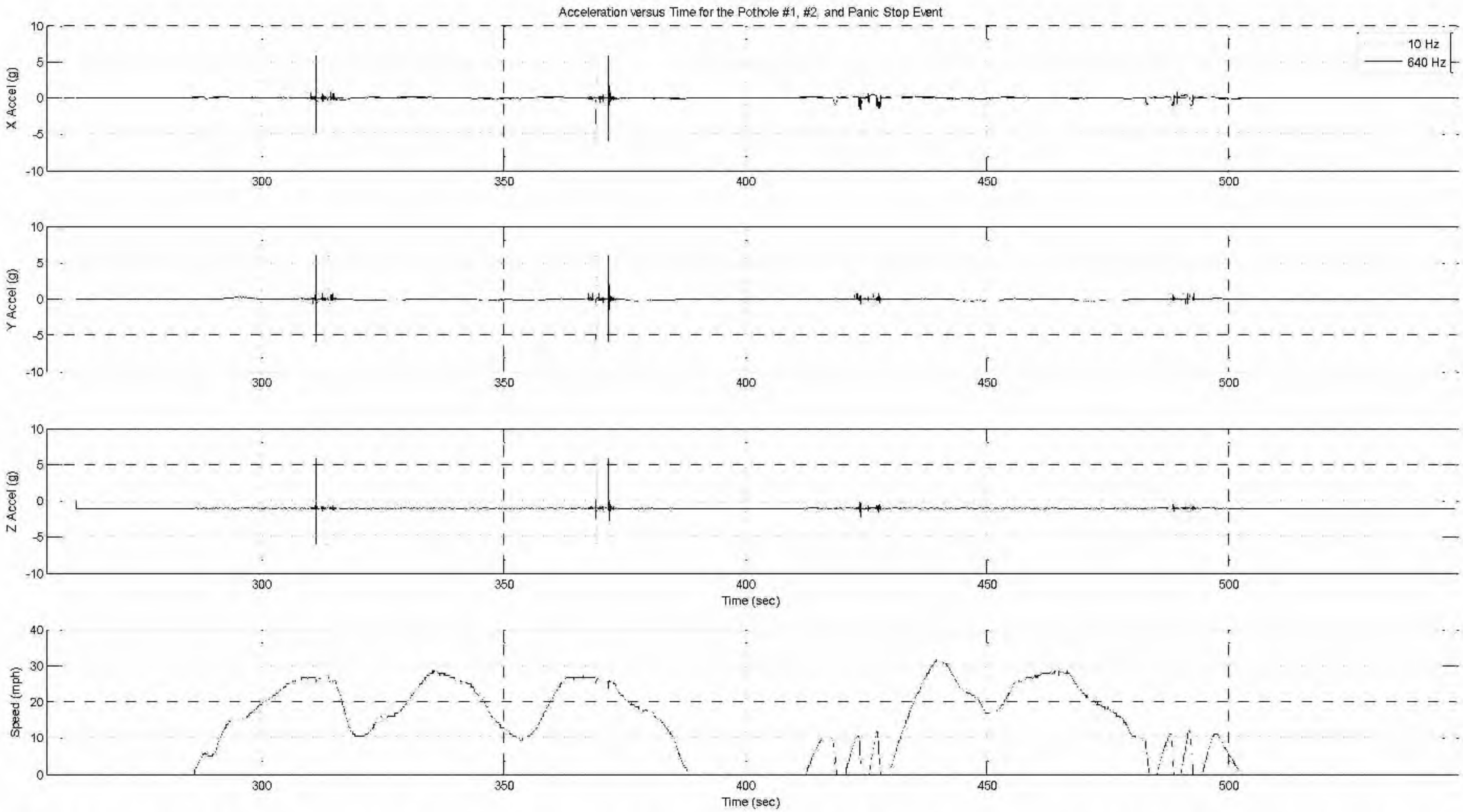


Figure 53. High- and low-speed 2006 Chevrolet Impala data recorded with VTTI DAS for Potholes #1 and #2 and Panic Stop tests.

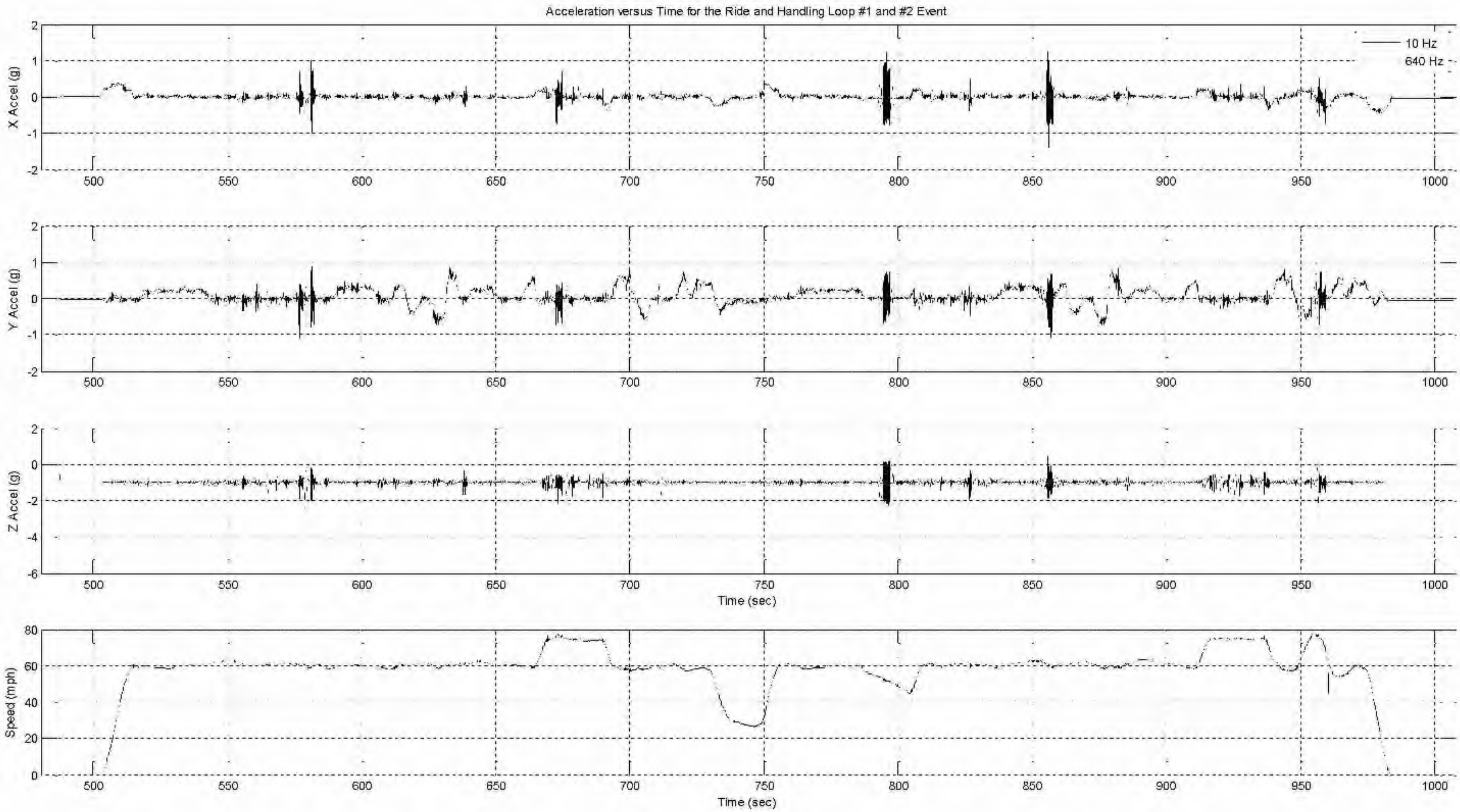


Figure 54. High- and low-speed 2006 Chevrolet Impala data recorded with VTTI DAS for Ride and Handling Loops #1 and #2 tests.

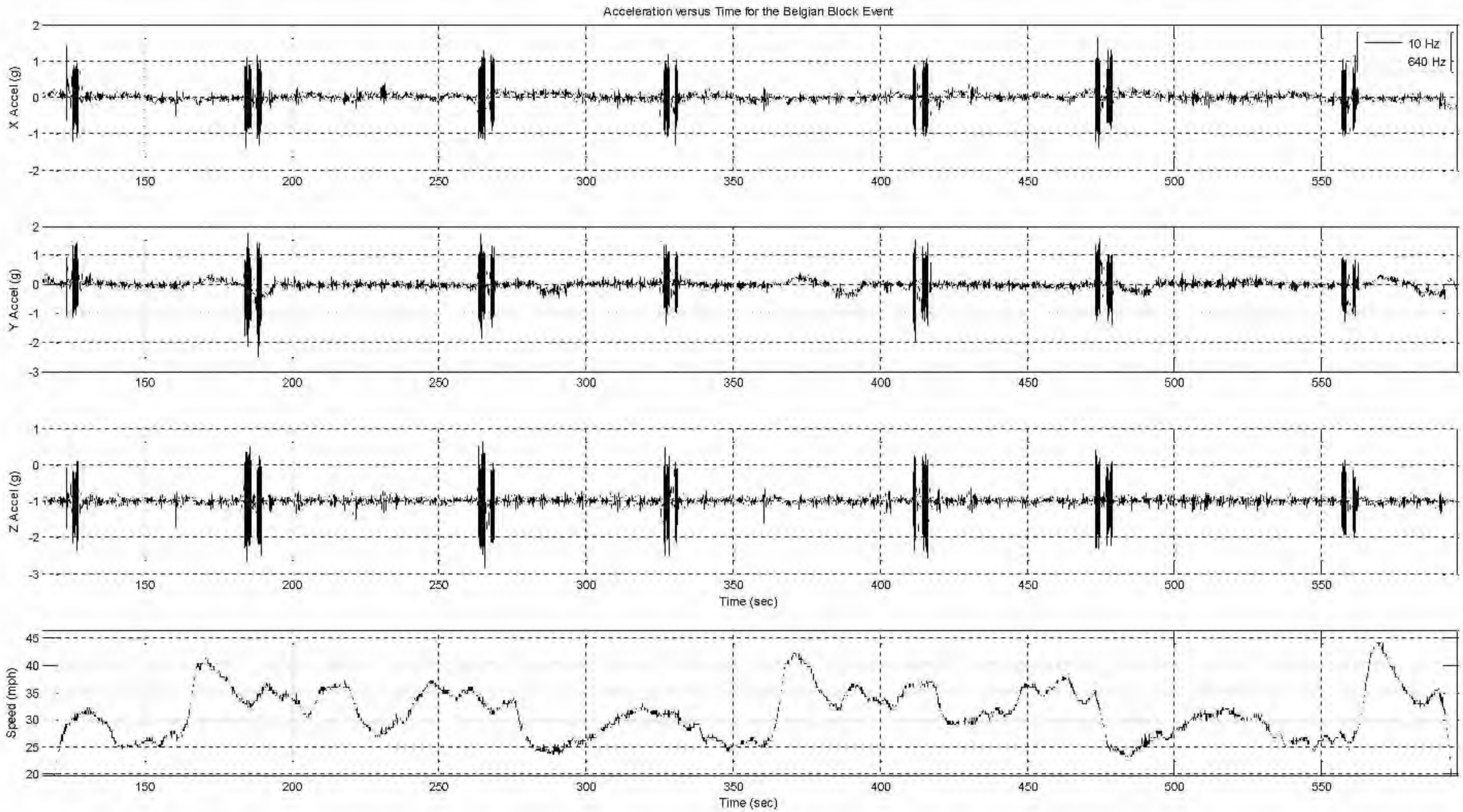


Figure 55. High- and low-speed 2006 Chevrolet Impala data recorded with VTTI DAS for Belgian Block test.

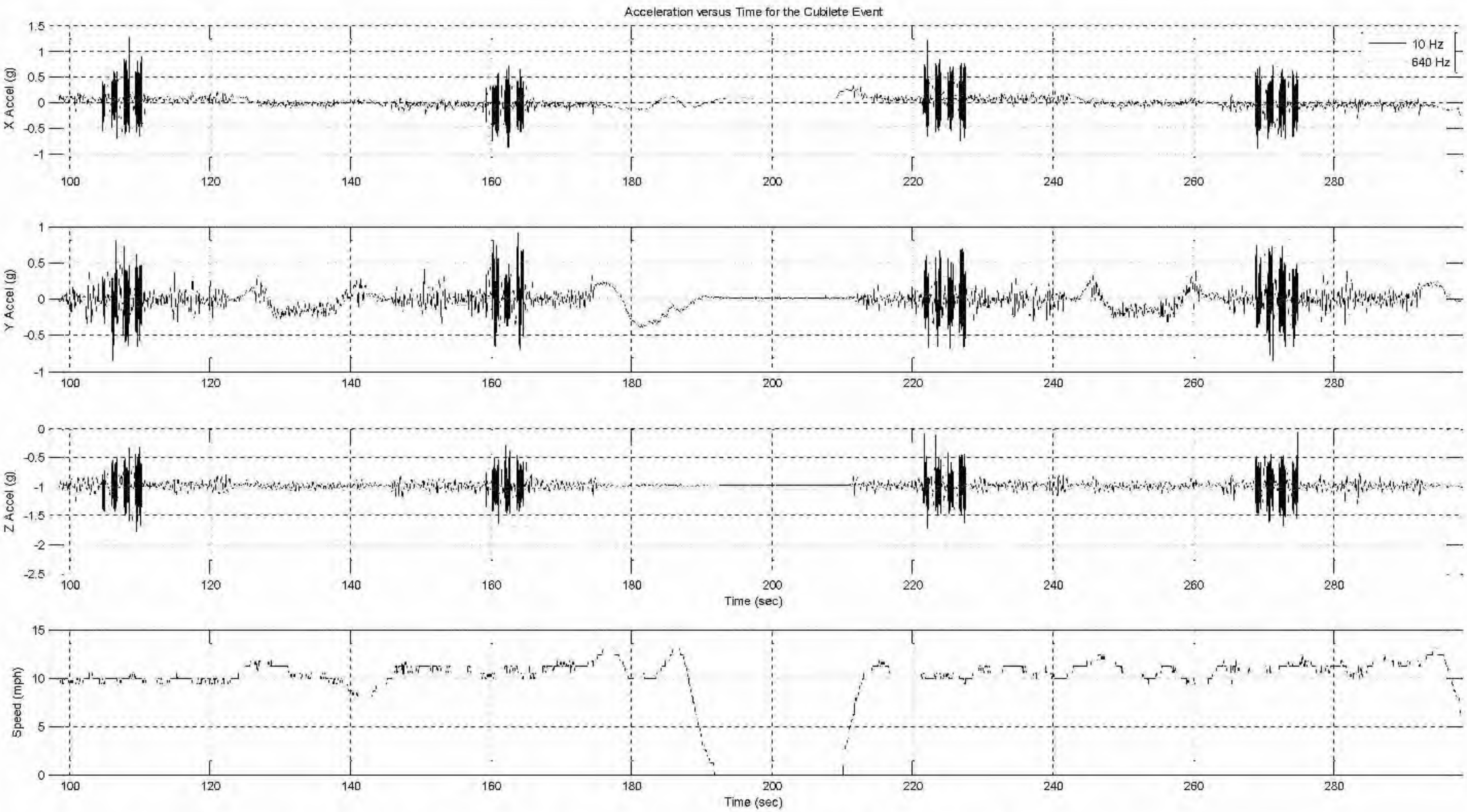


Figure 56. High- and low-speed 2006 Chevrolet Impala data recorded with VTTI DAS for Cubilete test.

Appendix D contains all of the cumulative frequency plots that compare the SHRP 2 NDS data to the data acquired at the GM MPG for the six sample vehicles across the longitudinal, lateral, and vertical accelerations. The cumulative frequency plots are given that show 99.9 percent of the data contained in the 0.05 percent to 99.95 percent range of the plot. The 99.9 percent data plots are shown below and are used for comparison; the outlying percentages are omitted within this section.

Figure 57 through Figure 59 illustrate the 99.9 percent cumulative frequency plots for the high-speed (640 Hz) data recorded during the Belgian Block test. Note that in all three acceleration plots (i.e., longitudinal, lateral, and vertical), the levels of acceleration throughout the entire cumulative percentage range are greater for the six tested vehicles than the acceleration levels found in the SHRP 2 NDS database.

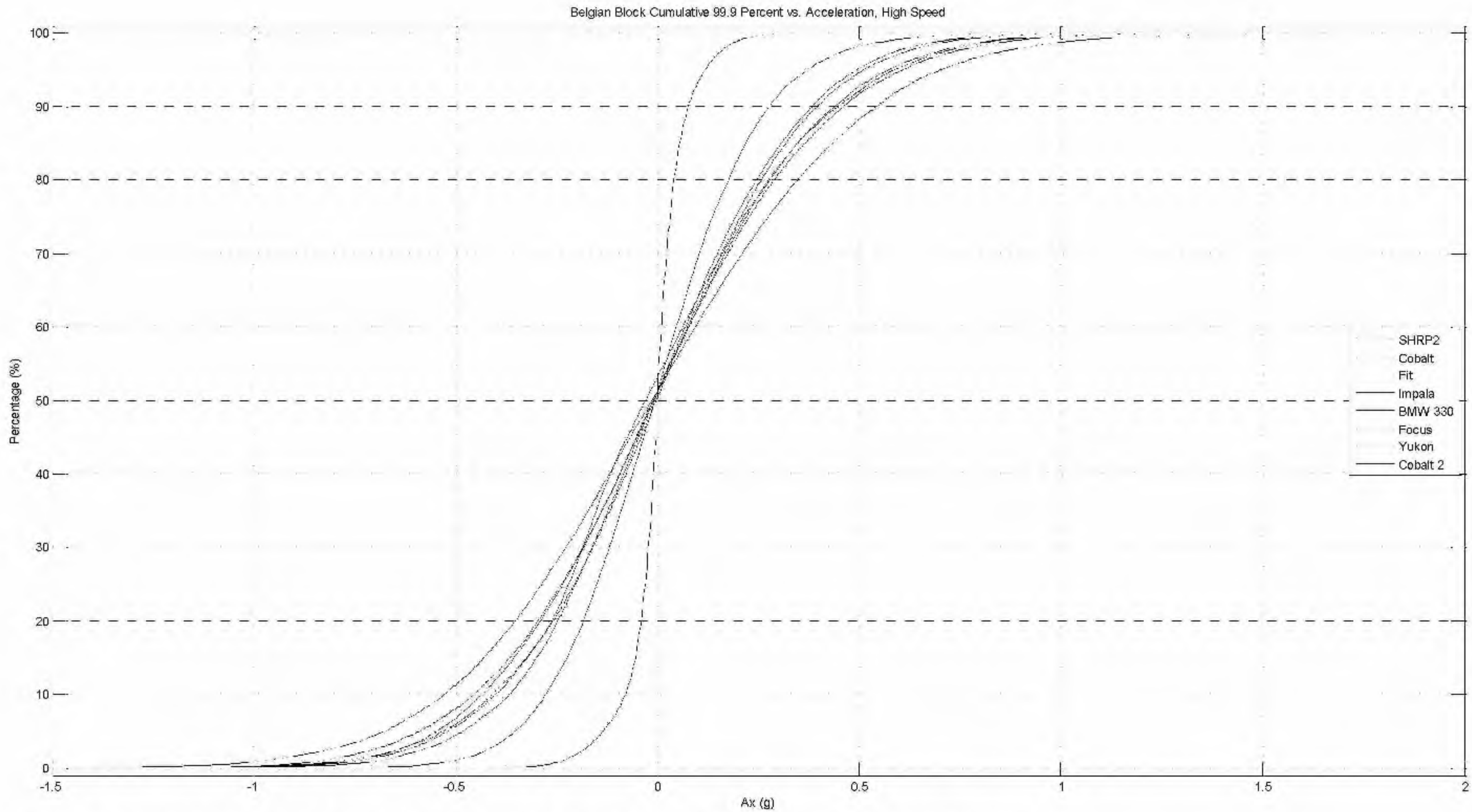


Figure 57. Belgian Block 99.9 percent cumulative frequency plot for longitudinal acceleration.

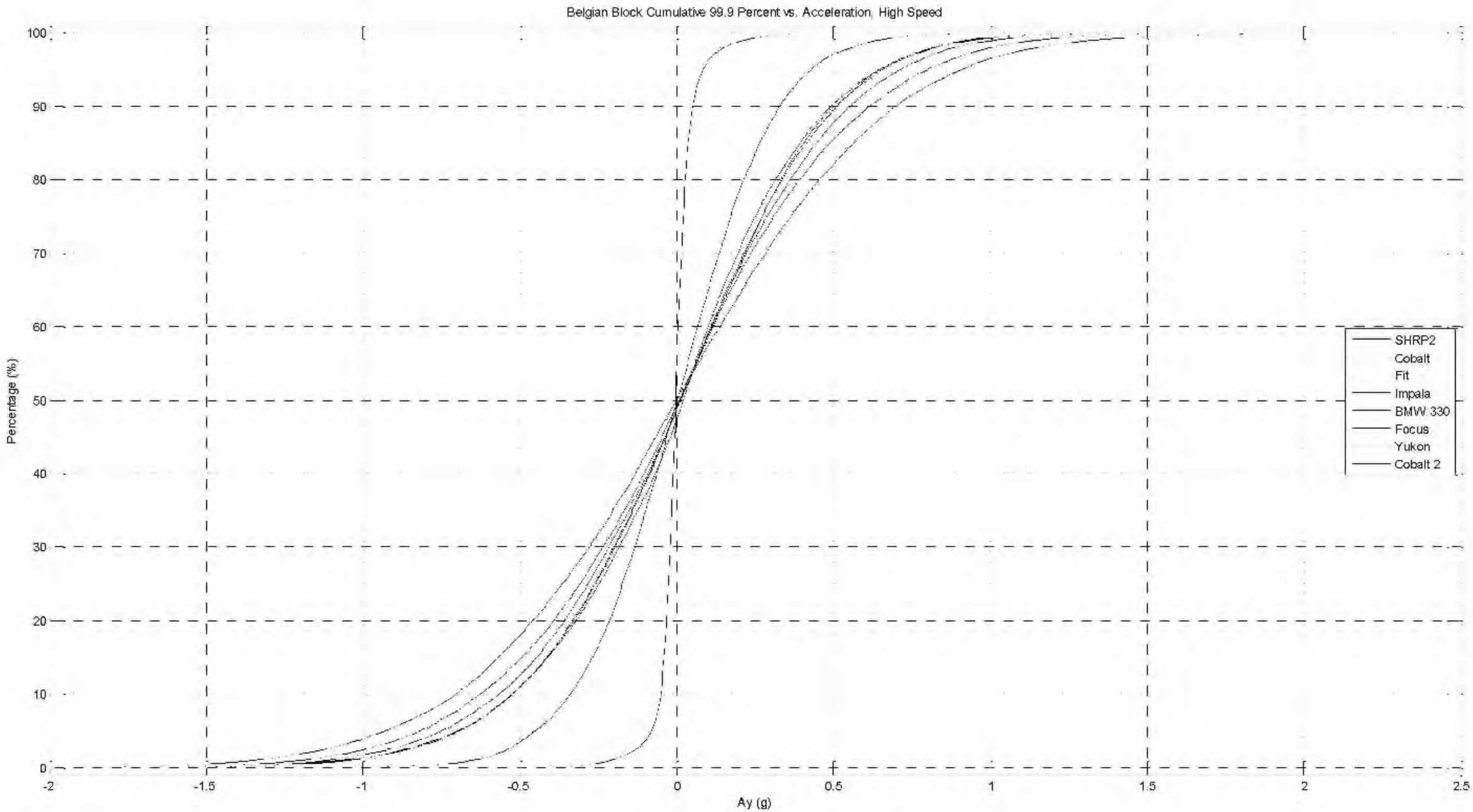


Figure 58. Belgian Block 99.9 percent cumulative frequency plot for lateral acceleration

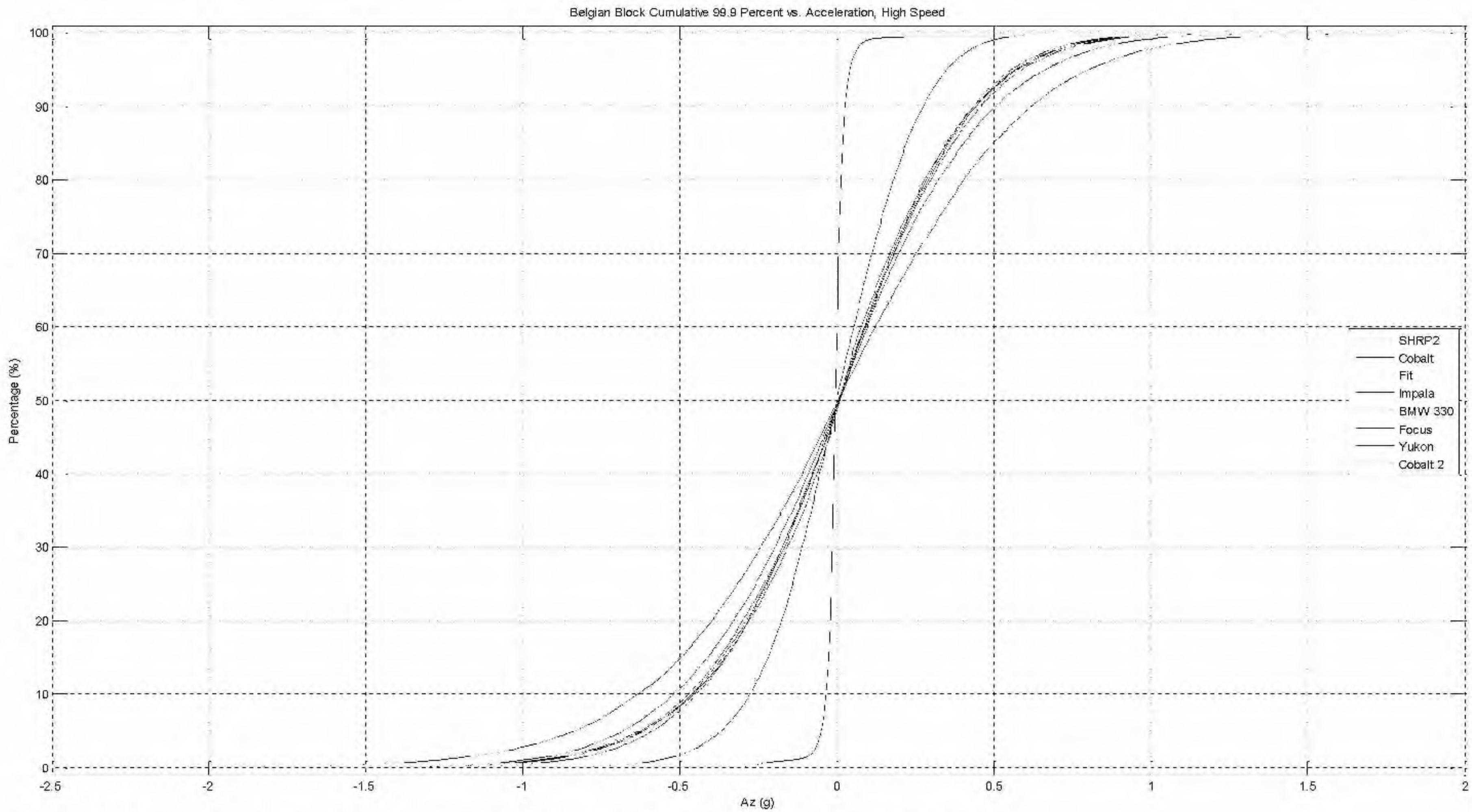


Figure 59. Belgian Block 99.9 percent cumulative frequency plot for vertical acceleration.

Figure 60 through Figure 62 illustrate the 99.9 percent cumulative frequency plots for the high-speed (640 Hz) data recorded during Ride and Handling Loops #1 and #2. It can be seen that the acceleration content in all three directions (i.e., longitudinal, lateral, and vertical) for each of the six vehicles tested on this event exceeds that of the SHRP 2 NDS data.

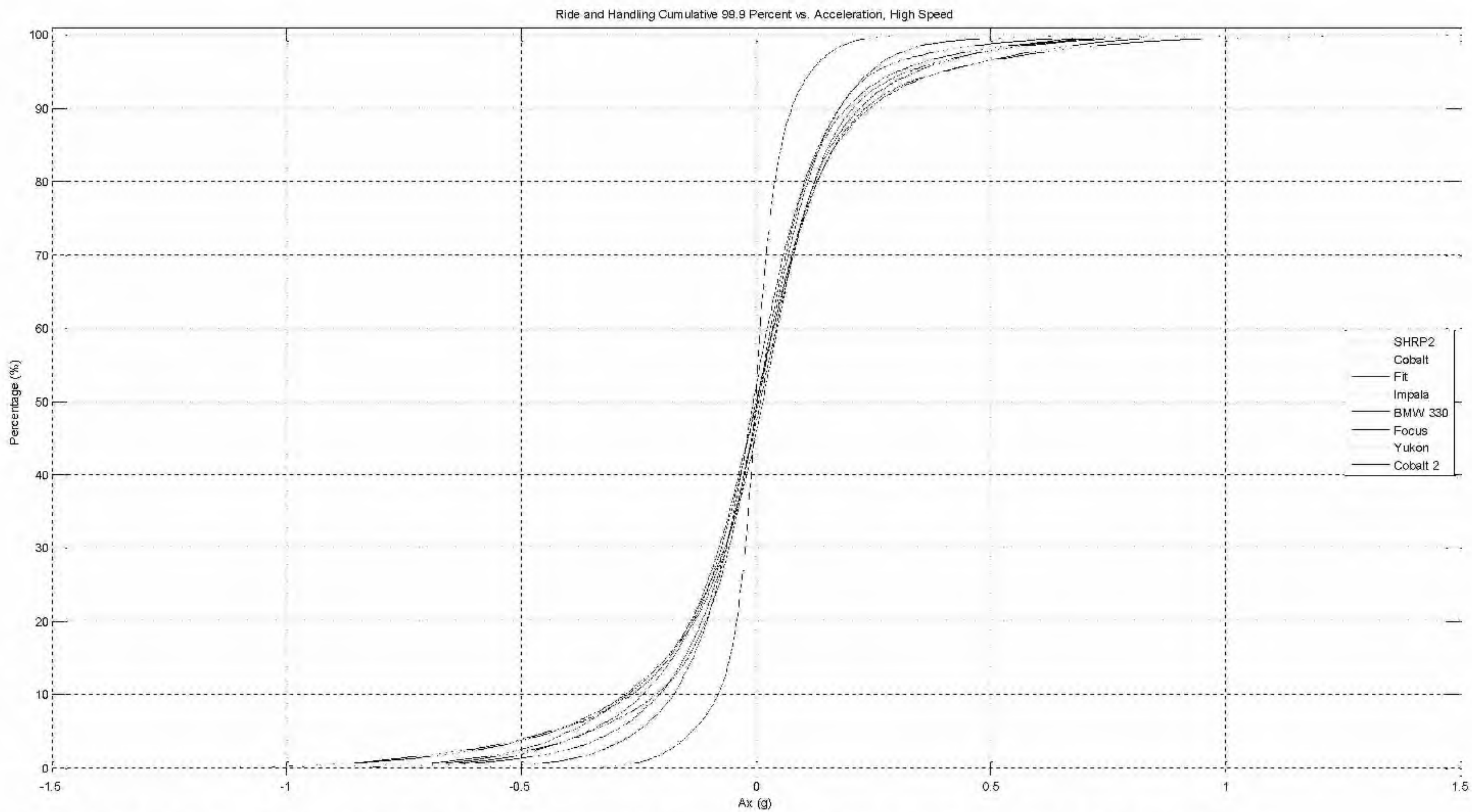


Figure 60. Ride and Handling Loops #1 and #2 99.9 percent cumulative frequency plot for longitudinal acceleration.

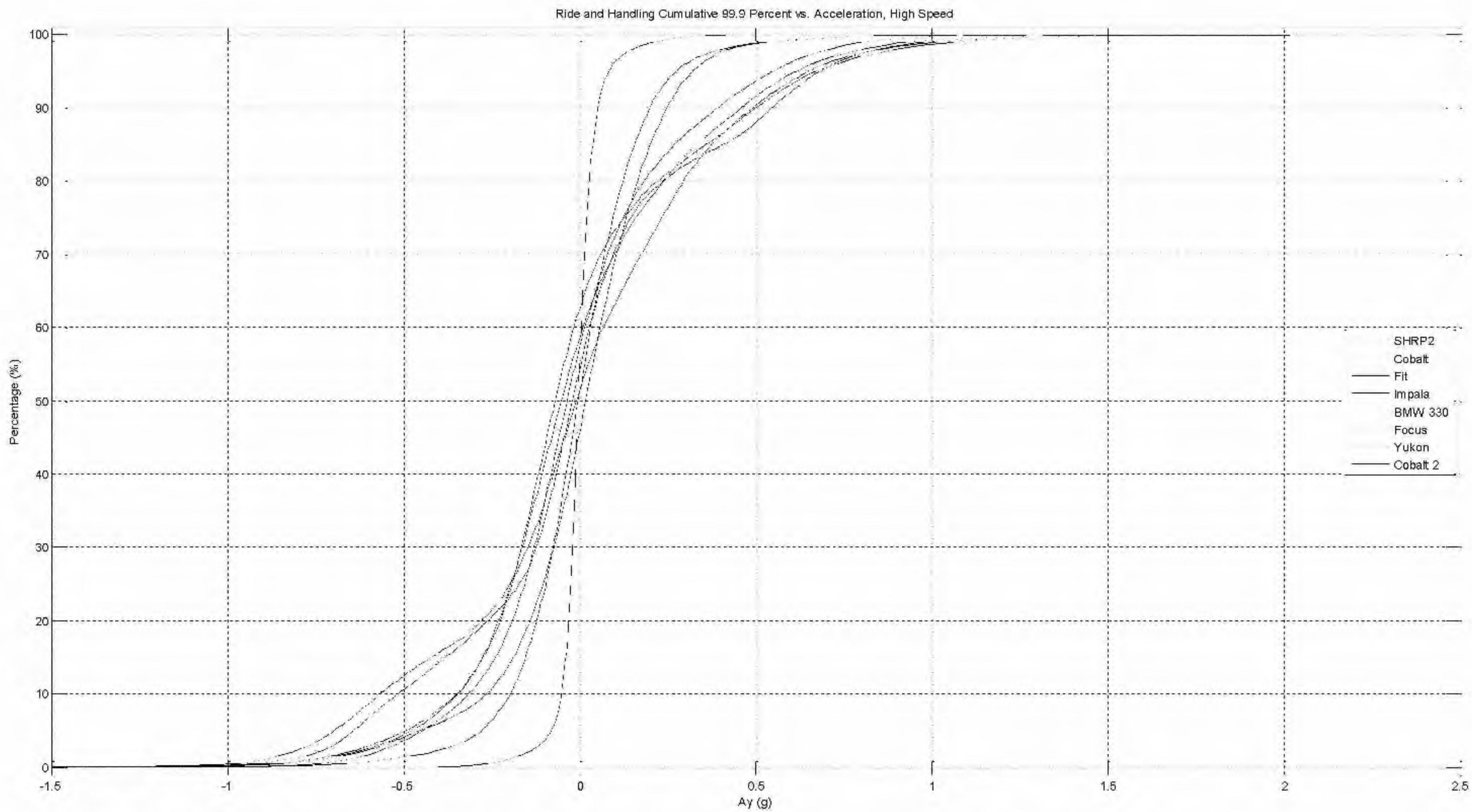


Figure 61. Ride and Handling Loops #1 and #2 99.9 percent cumulative frequency plot for lateral acceleration.

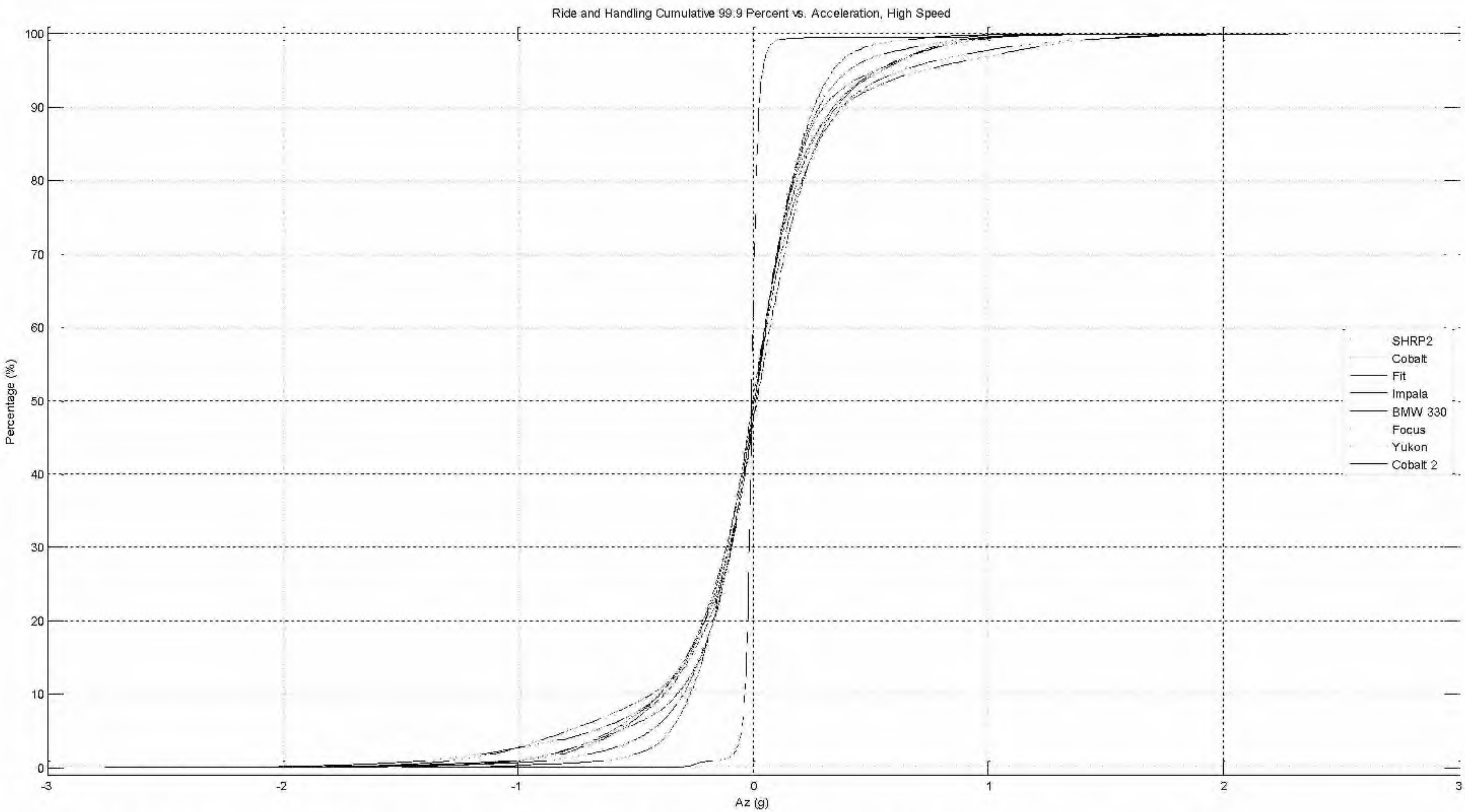


Figure 62. Ride and Handling Loops #1 and #2 99.9 percent cumulative frequency plot for vertical acceleration.

Figure 63 through Figure 65 show the 99.9 percent cumulative percentage plots for the high-speed (640 Hz) data recorded during Potholes #1 and #2 and the Panic Stop. A comparison to the SHRP 2 NDS data shows that the acceleration content for each of the six vehicles tested across these three GM MPG events exceeds the acceleration content reported in the SHRP 2 NDS database.

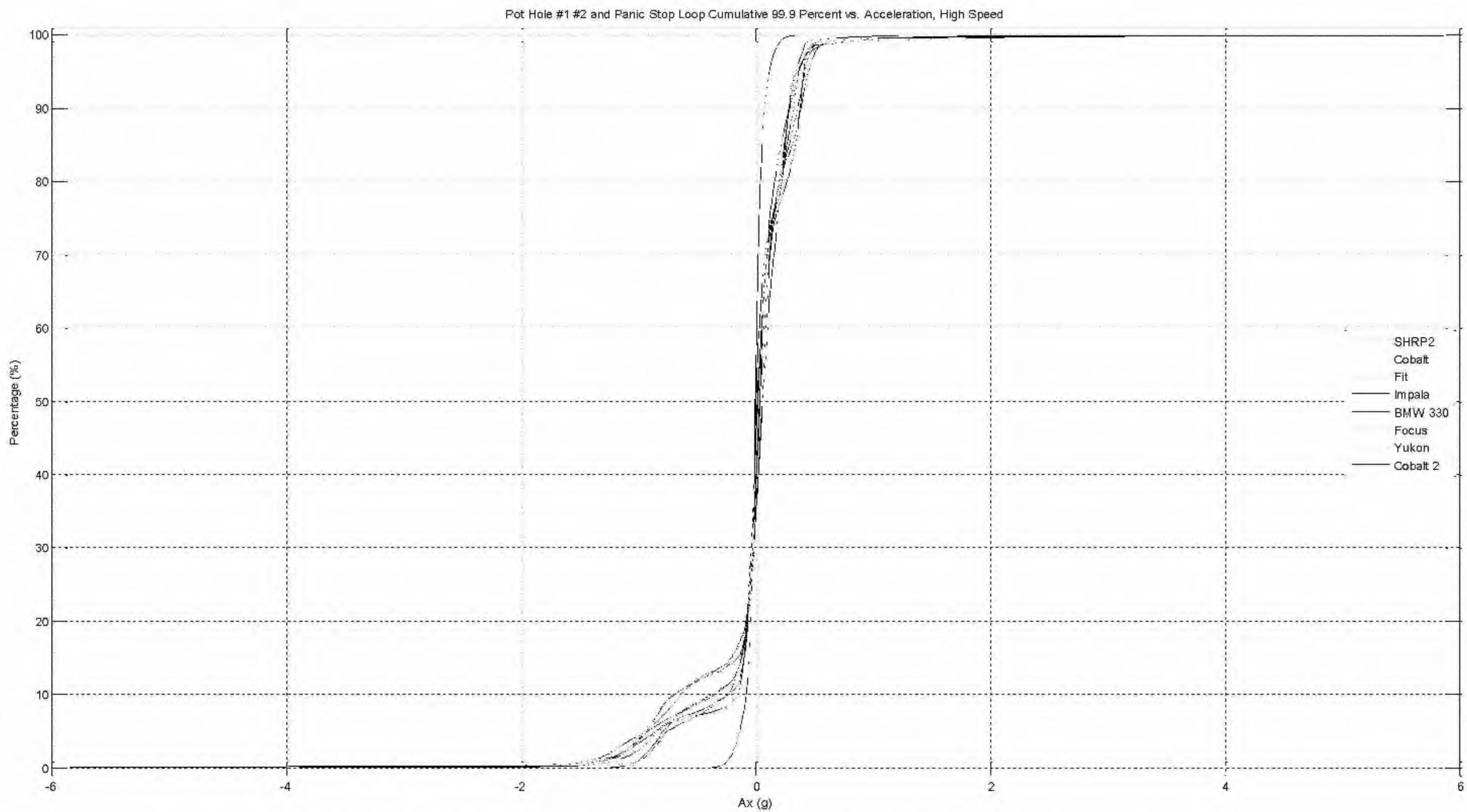


Figure 63. Potholes #1, #2 and Panic Stop 99.9 percent cumulative frequency plot for longitudinal acceleration.

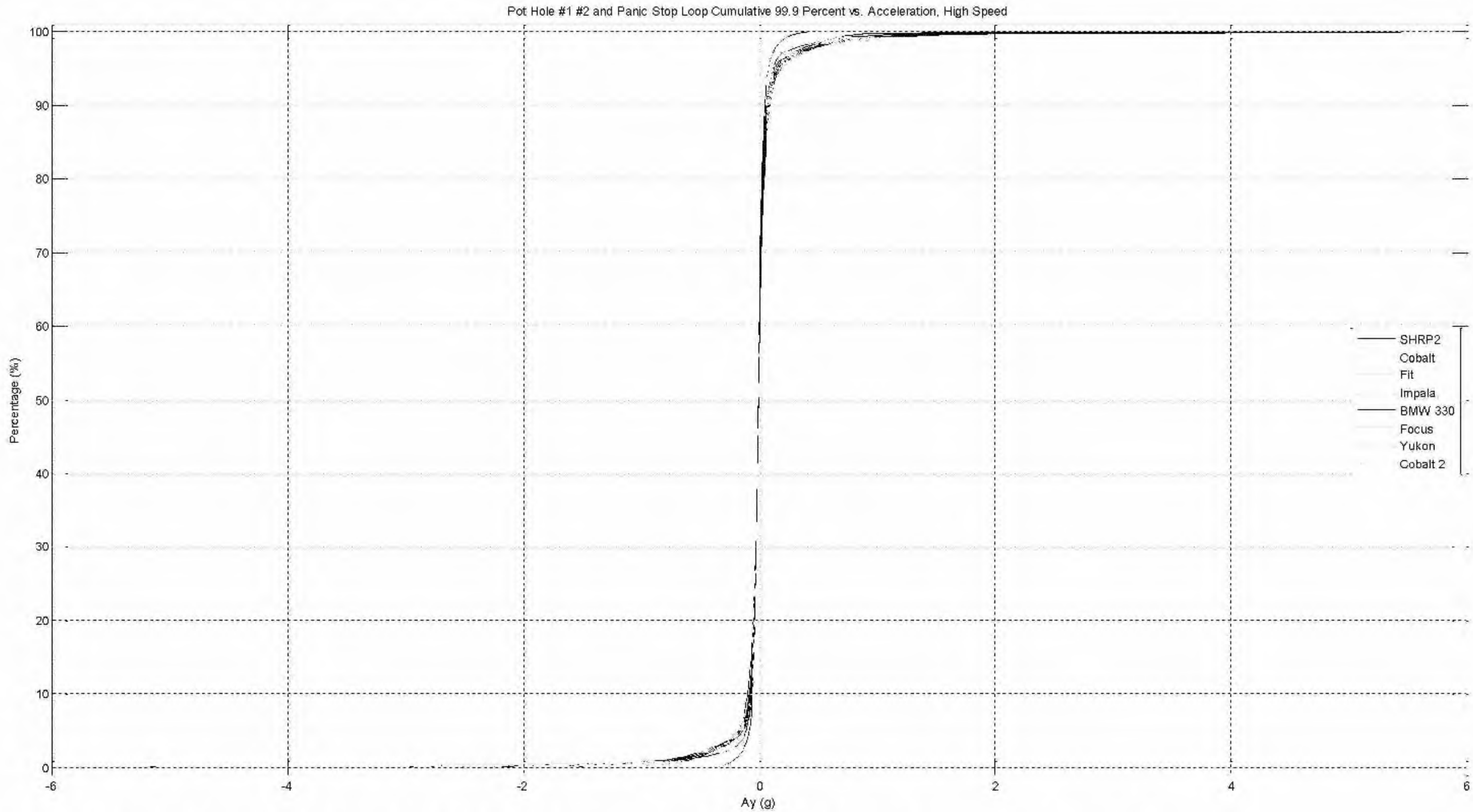


Figure 64. Pothole #1, #2 and Panic Stop 99.9 percent cumulative frequency plot for lateral acceleration.

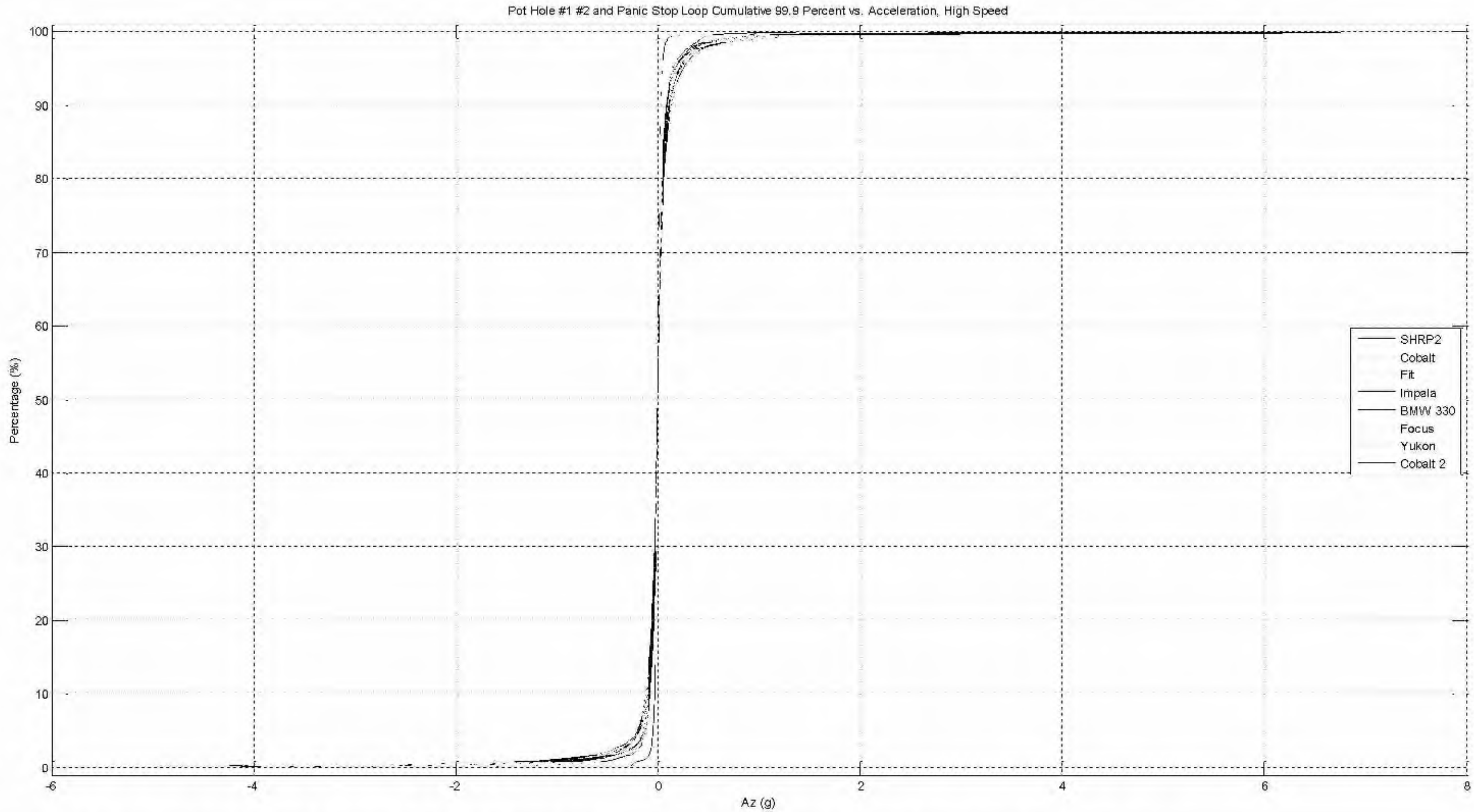


Figure 65. Pothole #1, #2 and Panic Stop 99.9 percent cumulative frequency plot for vertical acceleration.

Appendix D contains the full 0-100 percent plots and the 99.9 percent cumulative frequency plots for the low-speed (10 Hz) data. These plots present a complete picture of the comparative analyses performed using the SHRP 2 NDS data and the GM MPG data for this subtask. However, due to the low sample rate and the fact that, excluding the 2005 Chevrolet Cobalt, only one pass was recorded on each GM MPG event for the test vehicles instrumented with the VTTI DAS, the 10 Hz data did not provide an ideal basis for the cumulative percentage frequency plots. Therefore, such data were not presented within this section.

An acceleration comparison was also made between 312 off-road crash and near-crash events recorded in the SHRP 2 NDS database and the GM MPG events. The off-road events recorded in the SHRP 2 NDS database include driving off the road, over curbs, and driving into the median. Of the 312 off-road events, 18 triggered a high-speed recording feature of the DAS, thus indicating a potential crash event. Because of the time constraints associated with this project, the data associated with these high-speed, off-road events have not been thoroughly analyzed. However, the low-speed data from all 312 off-road events are provided below.

Figure 66 through Figure 68 illustrate the 99.9 percent cumulative frequency plots for the Belgian Block event. Note that, for all three accelerations (i.e., longitudinal, lateral, and vertical), the GM MPG Belgian Block acceleration content exceeds the acceleration content of the SHRP 2 off-road data. However, the difference between the GM MPG and SHRP 2 off-road data are minimal, particularly when compared to the on-road data analyzed above.

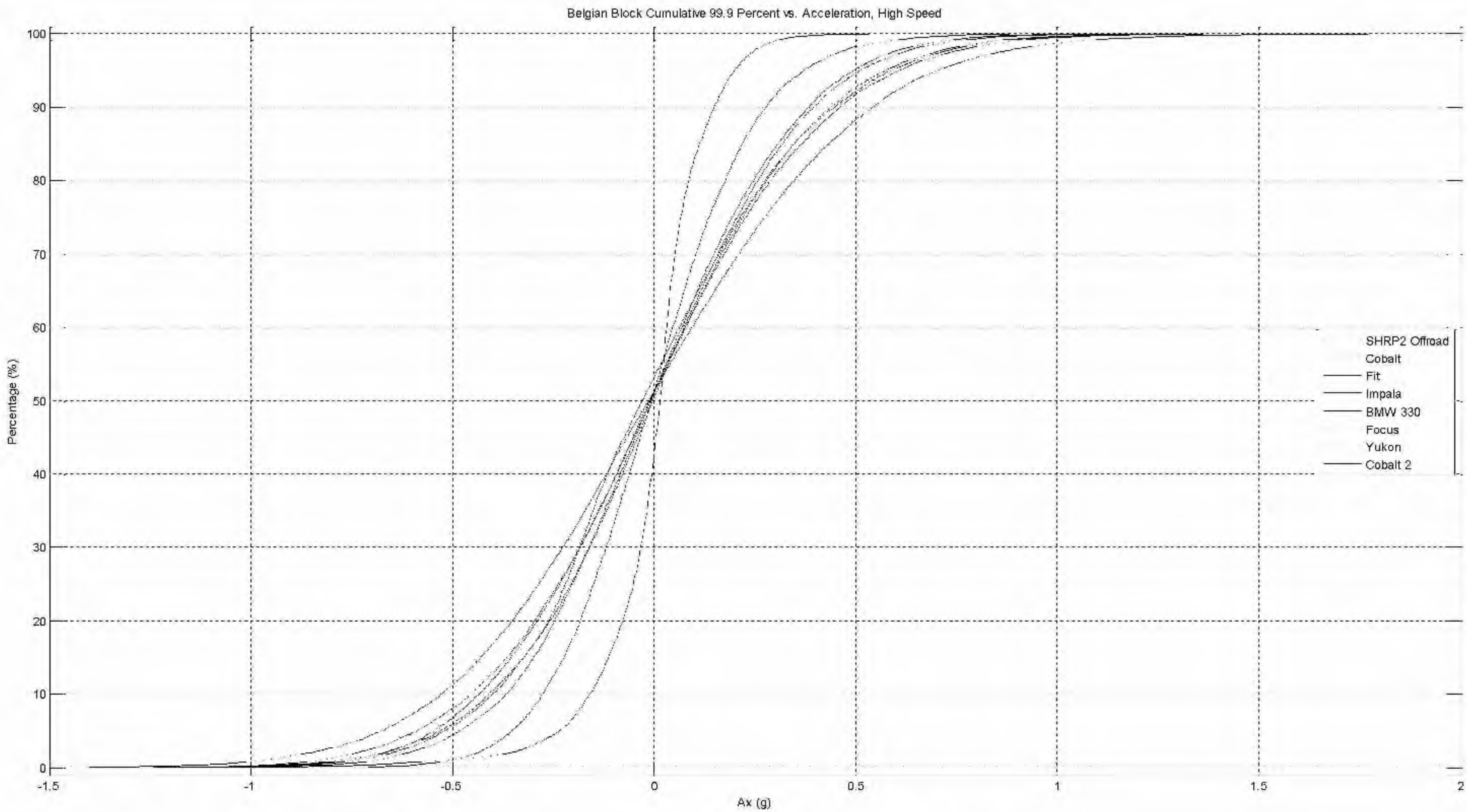


Figure 66. Belgian Block 99.9 percent cumulative frequency plot for longitudinal acceleration.

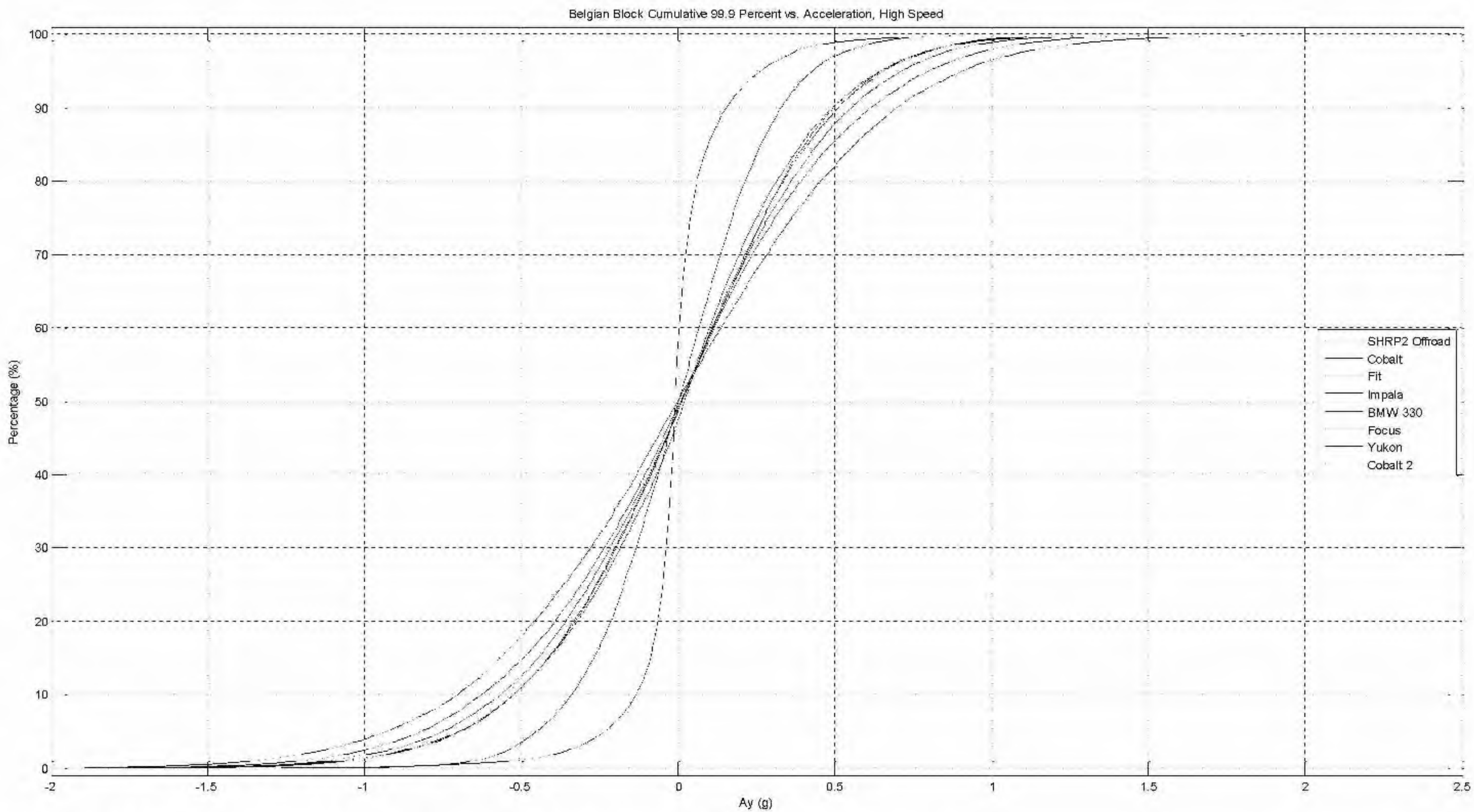


Figure 67. Belgian Block 99.9 percent cumulative frequency plot for lateral acceleration.

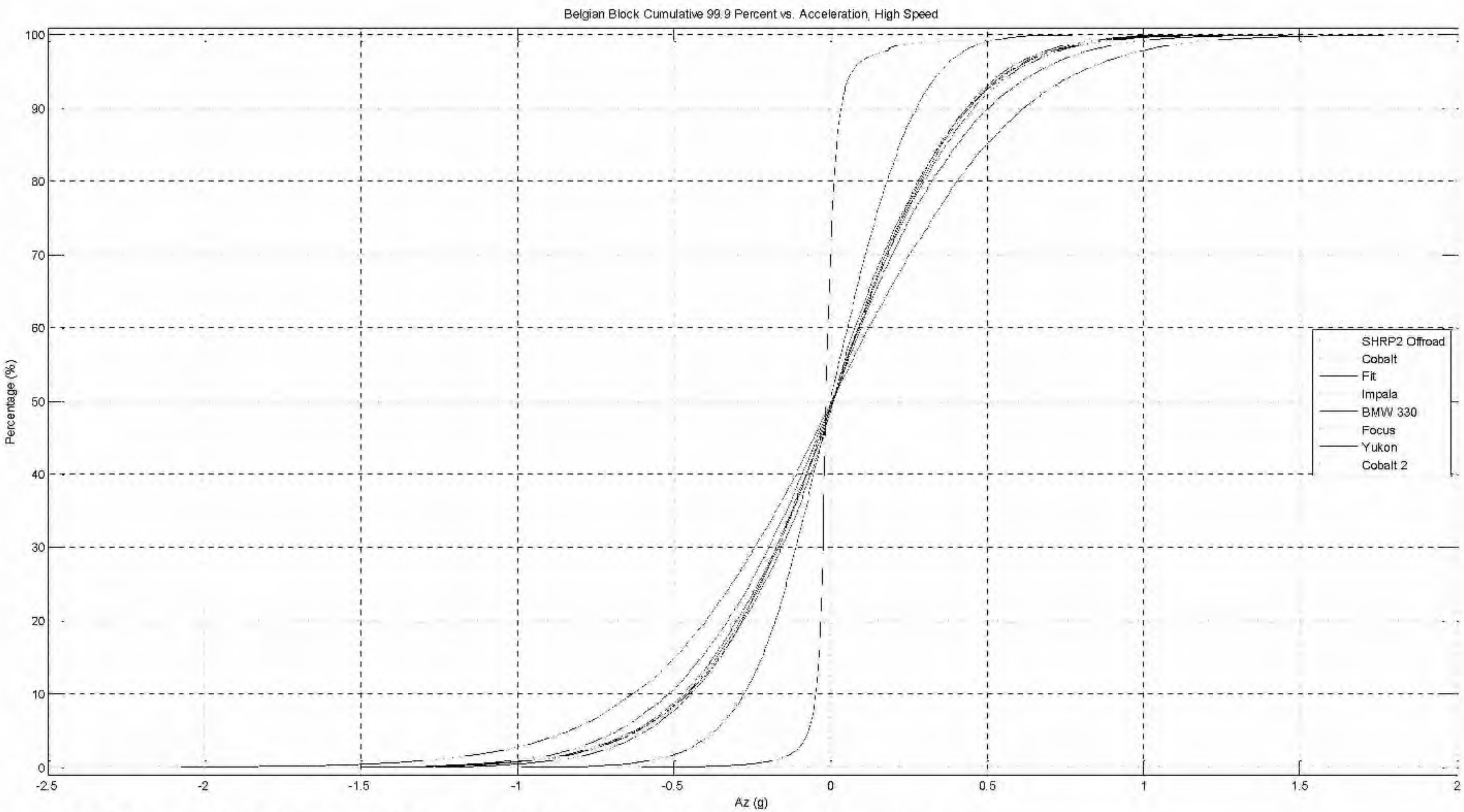


Figure 68. Belgian Block 99.9 percent cumulative frequency plot for vertical acceleration.

Figure 69 through Figure 71 show the 99.9 percent cumulative frequency plots for Ride and Handling Loops #1 and #2. A comparison between the GM MPG events and the SHRP 2 off-road data show there is comparable acceleration content between the data sets. It should be noted that there are regions within the plots where the SHRP 2 off-road data show more acceleration content. However, the acceleration content is generally higher for most of the vehicles tested across the GM MPG events.

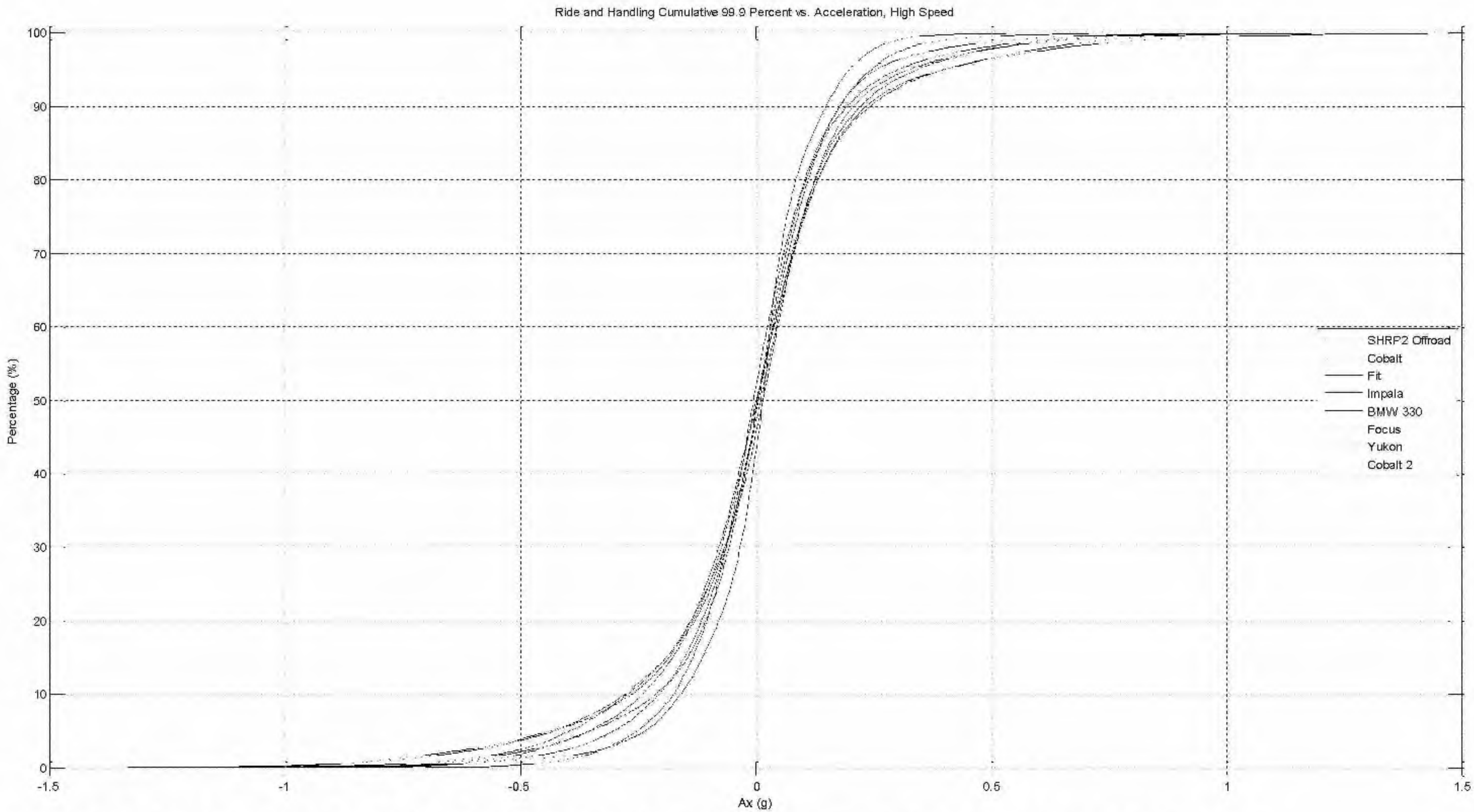


Figure 69. Ride and Handling Loops #1 and #2 99.9 percent cumulative frequency plot for longitudinal acceleration.

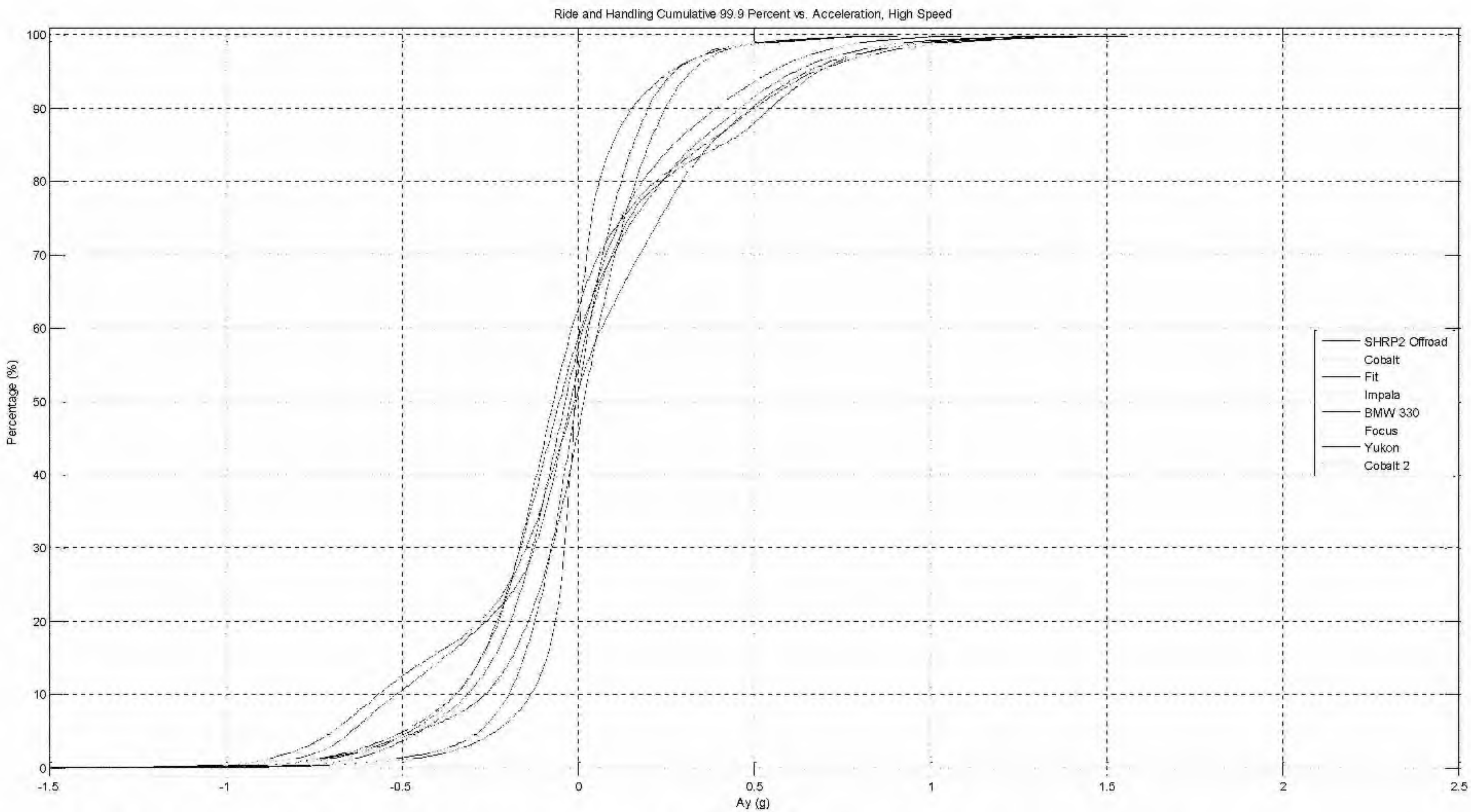


Figure 70. Ride and Handling Loops #1 and #2 99.9 percent cumulative frequency plot for lateral acceleration.

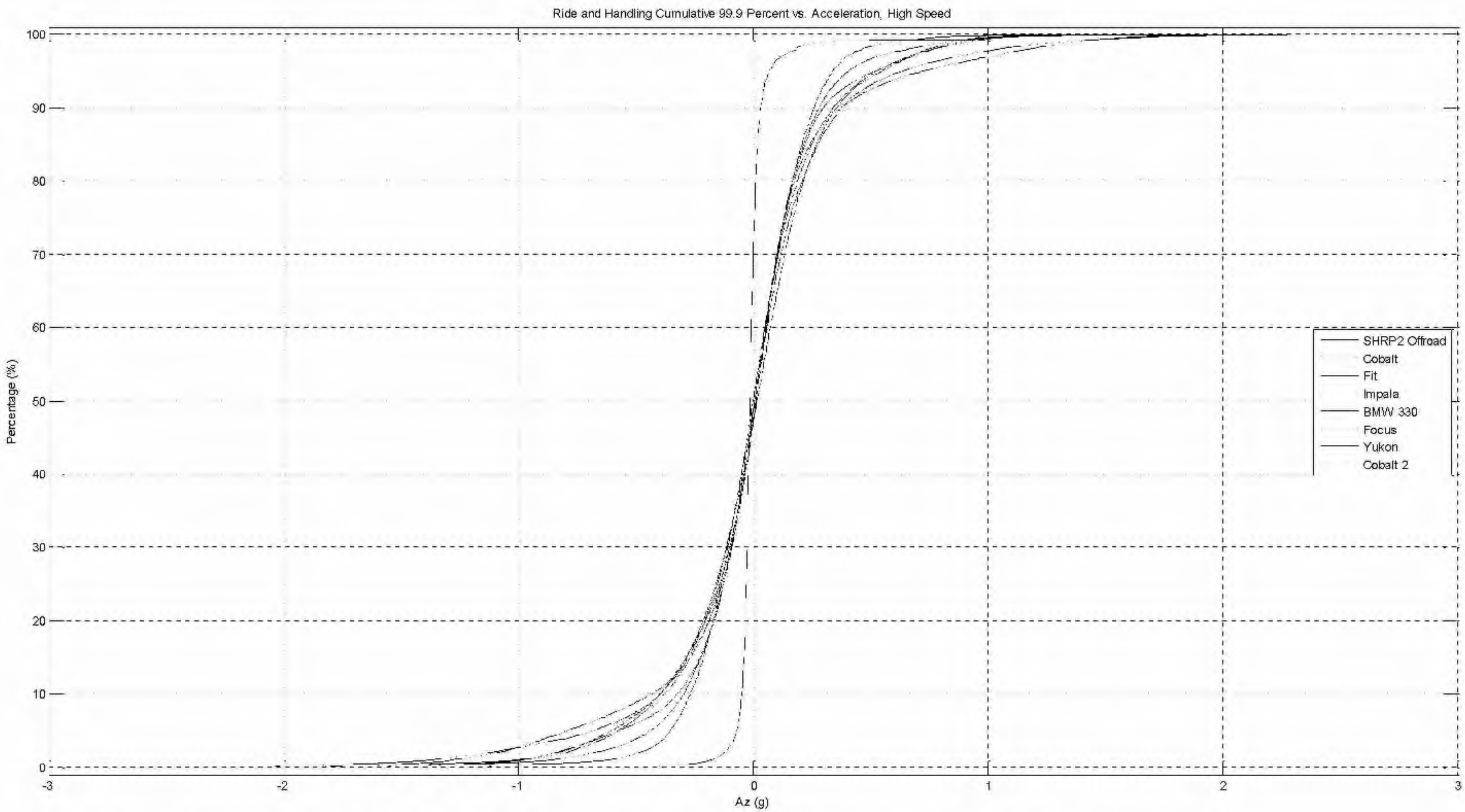


Figure 71. Ride and Handling Loops #1 and #2 99.9 percent cumulative frequency plot for vertical acceleration.

Figure 72 through Figure 74 illustrate the 99.9 percent cumulative frequency plots for Potholes #1 and #2 and the Panic Stop. As with the Ride and Handling Loops #1 and #2, there are portions of the plot where the SHRP 2 off-road data include more acceleration content than the GM MPG events. However, since these GM MPG events experience high accelerations during the pothole events and low accelerations elsewhere during the event, the extremes of the plot (i.e., 0.05 percent and 99.95 percent) are more significant and illustrate that these three GM MPG events provide greater acceleration input overall compared to the SHRP 2 off-road data.

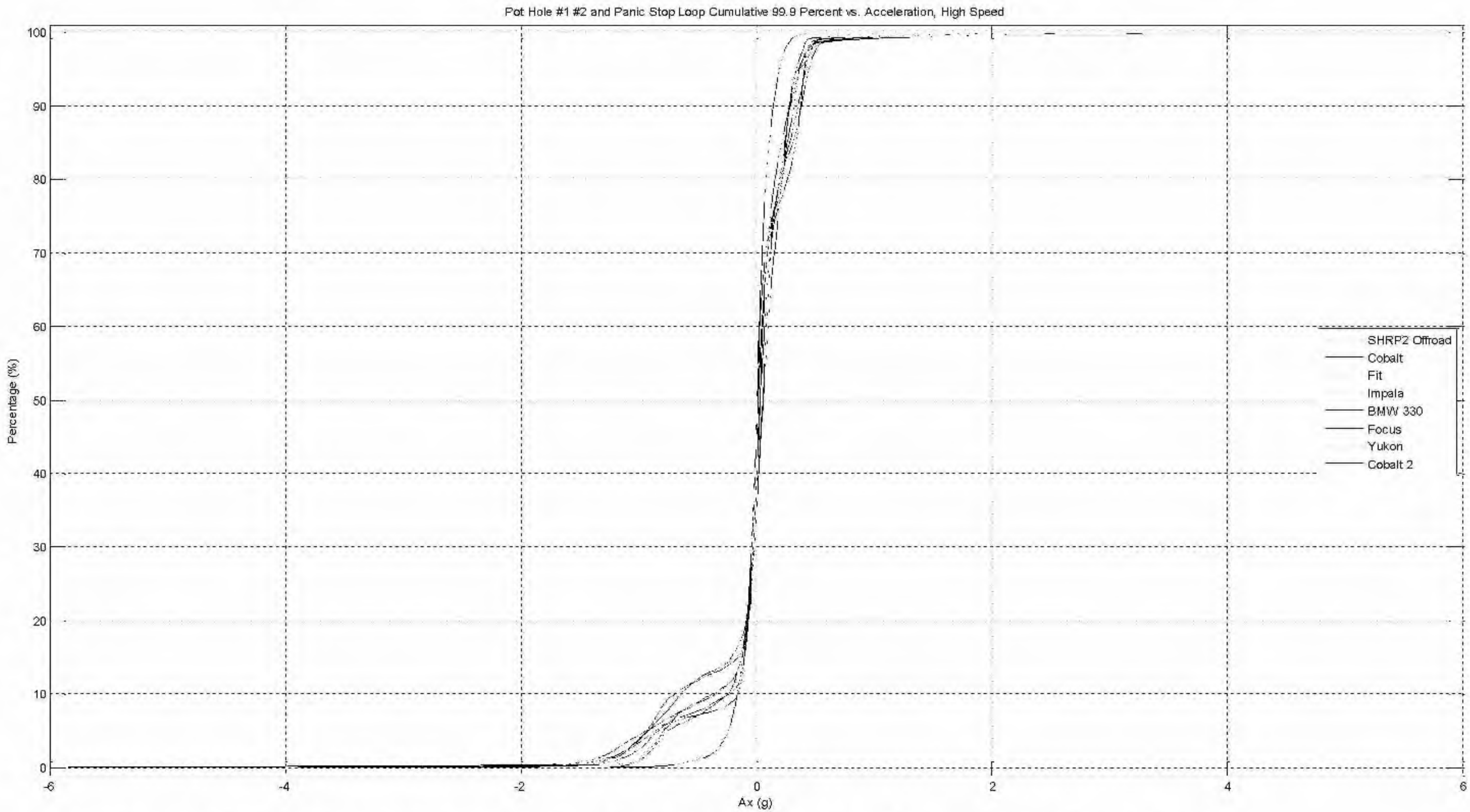


Figure 72. Potholes #1, #2 and Panic Stop 99.9 percent cumulative frequency plot for longitudinal acceleration.

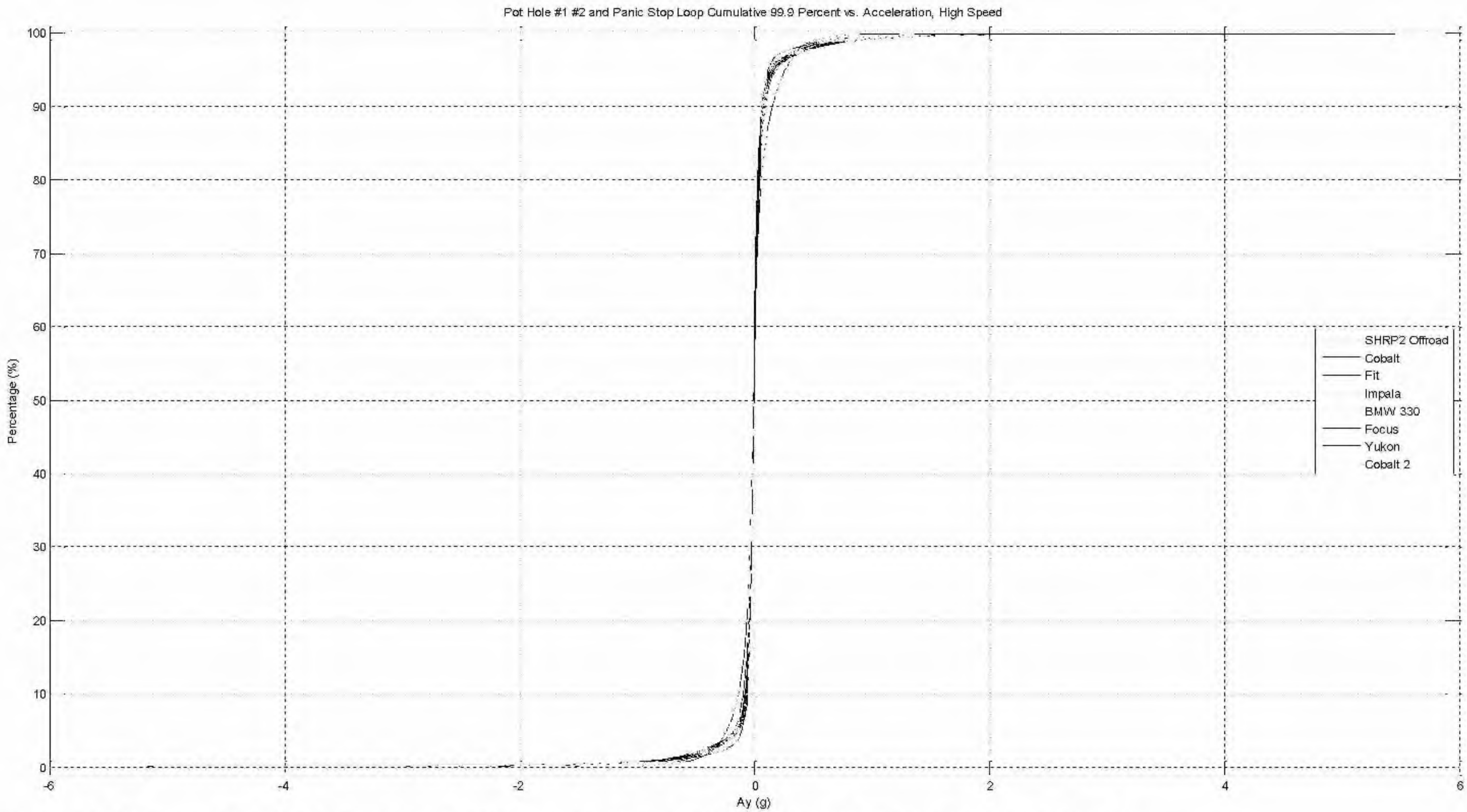


Figure 73. Potholes #1, #2 and Panic Stop 99.9 percent cumulative frequency plot for lateral acceleration.

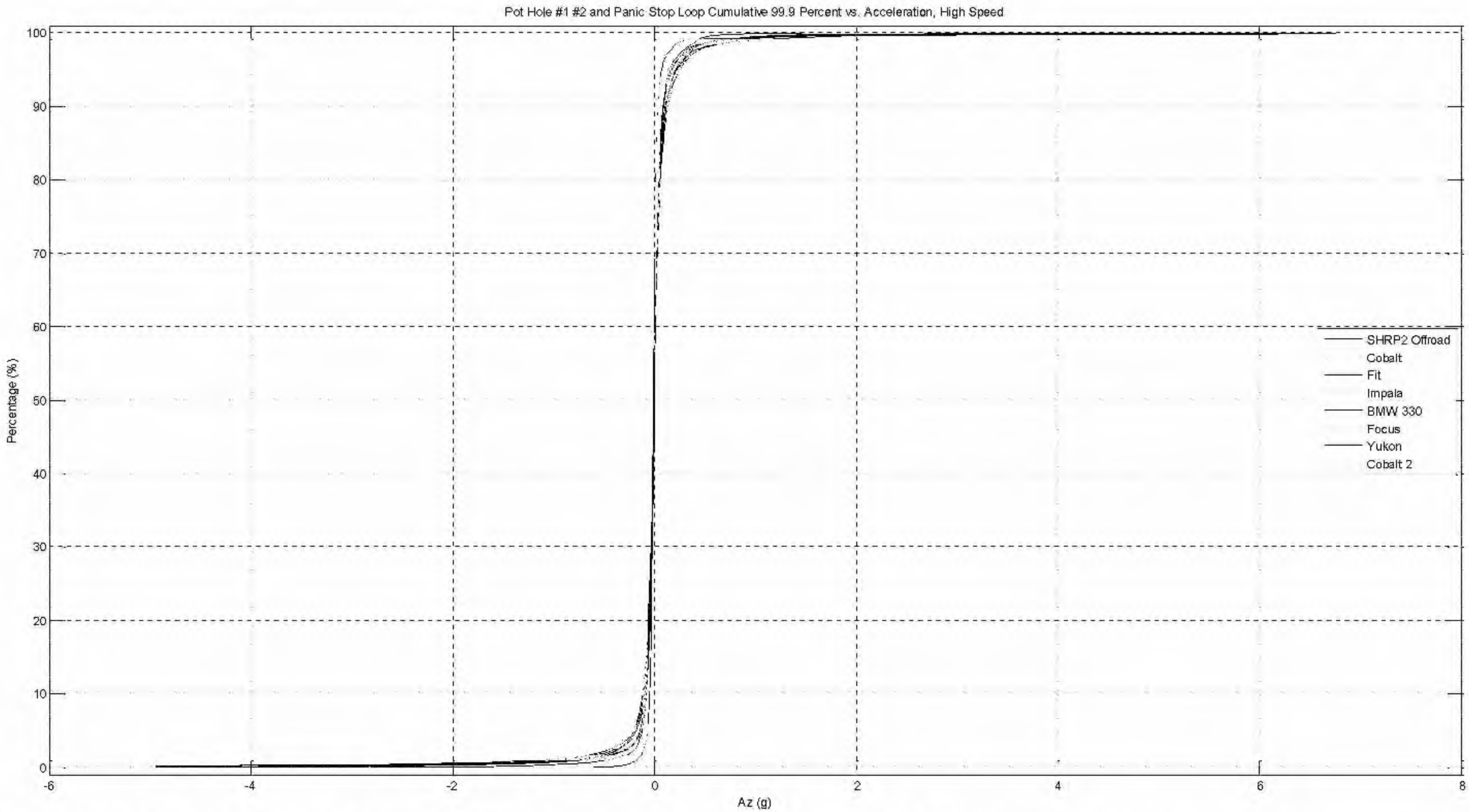


Figure 74. Potholes #1, #2 and Panic Stop 99.9 percent cumulative frequency plot for vertical acceleration.

Overall, comparing the GM MPG events to both the SHRP 2 on-road data and low-speed, off-road data showed that the GM MPG events capture and exceed the acceleration content seen in SHRP 2 NDS events.

Subtask 4: Validate Key Torque Measurements

GM uses the system-level key torque measurement as a metric to track the inertial performance of the ignition key. The system-level key torque measurements are important because they are a means of quantifying the static threshold torque required to move the ignition key from the "Run" to "Accessory" or "Off" position. However, during inertial acceleration events, the torque applied to the ignition key is dynamic and not static. Therefore, it is important to determine if the static measurement is a reasonable metric to track the ignition torque of the vehicle. Note that there is also a distinction between the torque required to move the ignition switch and the system-level key torque. That is, the torque necessary to rotate the ignition switch assembly as a separate component may be lower than the torque required to rotate the ignition key when the switch assembly is installed in the vehicle. As such, since inertial events produce a rotation torque while in vehicle, the system-level key torque is required.

GM uses two tools to measure system-level key torque. The first tool is a handheld unit that can be used to switch the vehicle ignition from the "Run" to the "Accessory" position. The device rotates the key very slowly, and the maximum torque measured during the motion is recorded as the threshold torque. A picture of the tool can be found in Figure 9. The second method is a bench-top test stand (Figure 10) where the ignition switch assembly is mounted in the test stand the same way it is mounted in the steering column of the vehicle. A handle is then used to rotate the ignition switch assembly from the "Run" to "Accessory" position, and the torque is measured. The bench-top test stand is inconvenient for measuring multiple vehicles, but it does allow for the measurement of the dynamic torque required to change the state of the ignition switch.

GM performed a dynamic torque study with a production 2006 Pontiac Solstice ignition switch assembly to assess the difference between static and dynamic key torque measurements. The dynamic key torque measurement was made by oscillating the switch handle mechanism between the 10-degree position and the 56-degree position, which correlates to moving the ignition switch from "Off" to "Accessory" and from "Run" to "Crank" and back through the states to "Off." The handle was moved in a sinusoidal manner (i.e., in the form of a wave) at multiple frequencies, from 0.1 Hz to 7 Hz. Figure 75 shows a plot of the switch angle and switch torque for one cycle from each oscillation frequency. As the sinusoidal frequency increases, the amount of peak torque required to move the ignition switch out of the "Run" position to the "Accessory" position increases. However, as the oscillation frequency increases and the peak torque is achieved, the amount of torque required to continue moving the ignition switch decreases. This indicates that, as the input switch frequency is increased, the torque required to begin the movement from the "Run" position increases. However, once moving, the amount of torque required to maintain the motion decreases. Therefore,

short-duration dynamic torques that are greater than the static torque can cause unintended ignition key rotation.

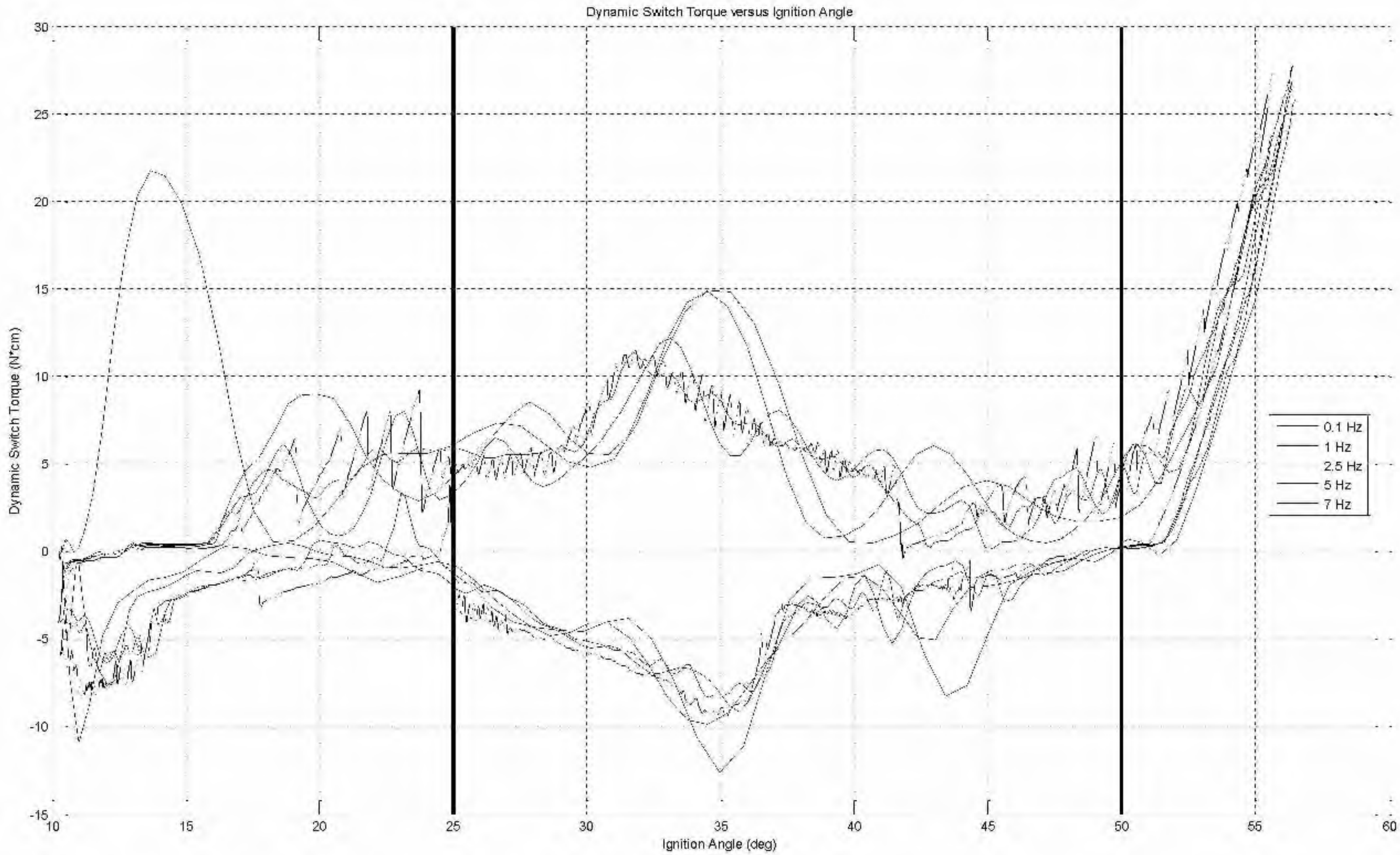


Figure 75. Dynamic torque vs. switch angle for sinusoidal input to ignition switch across various frequencies.

The VTTI project team recommends verifying the dynamic torque finding by applying an impulsive change in the ignition switch position to move the key from "Run" to "Accessory." A partial sinusoidal change in the switch position could be used and the frequency varied. The measured dynamic torque profile could then be compared to the results provided herein to verify the dynamic torque findings.

Since the static torque provides the lowest value regardless of duration (i.e., the worst-case torque value), it is a reasonable metric to use as the threshold torque for determining an unintended ignition key rotation. It should be noted that, once a large number of vehicles have been measured for static torque and evaluated across the GM MPG, a database of results correlating threshold torque to vehicle class, inertial test results, and other properties may be developed. This database could then be used to predict unintended key rotation and possibly eliminate physical testing on the GM MPG.

Subtask 5: Perform a Key Chain Analysis

The VTTI project team and GM performed separate sample studies to understand the length and weight of items that drivers hang from their ignition keys. Such an understanding is important relative to inertial effects that may cause an unintended change in the ignition switch position. The GM study included 502 key chain measurements; the VTTI study comprised 60 key chain measurements (Appendix B). The results of the statistical analysis can be found in Table 6.

Table 6. Statistical Analysis of the GM and VTTI Key Chain Studies.

	GM	VTTI
Maximum Weight	0.61 lbf	0.5 lbf
Mean Weight	0.18 lbf	0.23 lbf
Maximum Length	42 cm	52 cm
Mean Length	12.23 cm	13.7 cm
99% Weight	0.44 lbf	0.47 lbf
99% Length	29 cm	51.2 cm

Note that most of the VTTI statistical values closely match the GM statistical values, excluding the 99 percent length data. To calculate the 99 percent value, the cumulative percent of frequency was generated for the key chain weight and length, and the 99 percent value was estimated from the data. However, only 23 different values were reported in the key chain length calculation made using the VTTI data, so the outlier lengths have a strong effect on the result. If a normal distribution of data is assumed, the 99 percent key chain length value calculated for the VTTI study is 33.9 cm, which is closer to the value reported by the GM study.

As discussed, GM performs its inertial tests using a maximum key weight of 0.7 lb, which exceeds the maximum weight measured in both key chain studies. The 0.7 lb weight exceeds the maximum GM weight found during the key chain analysis by approximately 15 percent and the mean weight by a factor of 3.89. Based on the predictive model discussed during Subtask 2, this larger mass will produce a larger inertial response at the ignition key and will exaggerate the inertial effect on unintended ignition key rotation. The larger mass also obviates the need for a maximum key chain length during the GM inertial test. Long key chains will impede the pendulum motion of the key mass through an interaction with the driver's legs, the dash, and/or the steering column. When the long key chain is not impeded, the pendulum-like swing induced by the key ring length produces a gyroscopic force that acts to rotate the ignition key that is proportional to the key ring length, as seen in the predictive model. Therefore, an exaggeration of the mass allows for the use of a shorter key ring length during testing to produce the same gyroscopic effect.

Subtask 6: Key Ring Binding

Key ring binding can become an issue when considering inertial effects that may result in an unintended key rotation. The predictive model discussed in Subtask 2 shows that the torque acting on the ignition key to potentially move it out of the "Run" position is proportional to the inertial force generated by the key ring hanging from the key. This is multiplied by the distance of the key ring from the center of the key. If the key ring binds on the key, the effective distance at which the inertial force is applied to the ignition key head can increase, producing a greater inertial torque and a possible unintended ignition key rotation.

If the key ring is larger than the head of the ignition key, the ring may wrap around the key head and bind along the edge or on the corner of the ignition key. In this scenario, an ignition key with a hole design in the key head could still possibly experience an unintended key rotation if the key ring binds improperly around the corner or edge of the ignition key head. A possible solution to this problem would be the use a key ring that is smaller than the ignition key head. Figure 76 illustrates the key ring binding problem and possible solution. Note that, in the top pictures, the key ring can wrap around the head of the ignition key and possibly bind against the head of the key. The perpendicular length from the center of the key to the point where the key ring binds defines the distance from the center of the key where the inertial force acts. With the recommended solution in the bottom drawing, the key ring cannot bind with the corner or edge of the ignition key, thus minimizing the inertial force acting on the ignition key head.

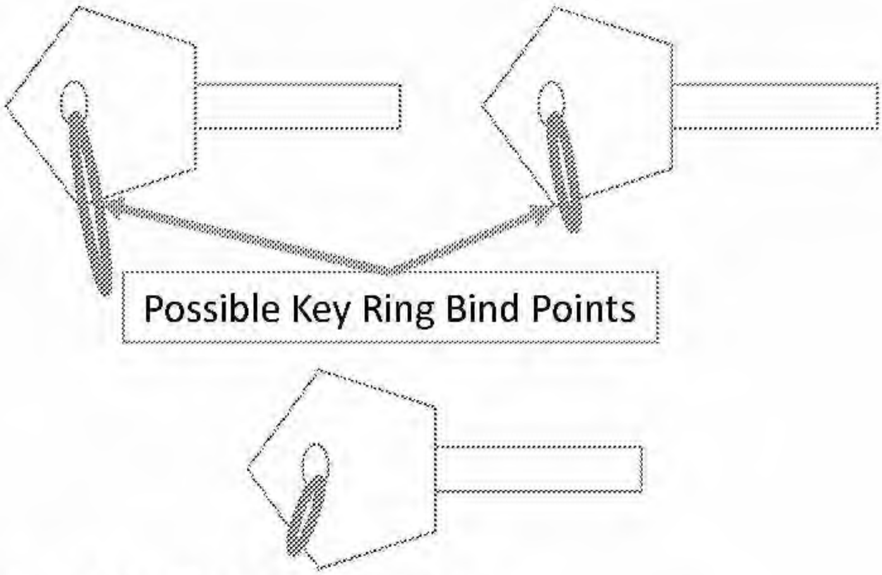


Figure 76. Diagram of key ring binding scenarios.

Subtask 7: Review SHRP 2 NDS Video for Inertial Events

As discussed previously, the SHRP 2 NDS database was queried in search of cases during which the ignition state was unintentionally altered due to inertial factors. To accomplish this goal, a basic query flagged trip files during which the ignition state moved out of the "Run" position adjacent (i.e., within approximately one second) to a speed greater than or equal to 5 mph. Due to the use of such a liberal query, the majority of reviewed events included an observed purposeful ignition-off by the driver (e.g., at the end of a trip). However, it was decided not to further refine the query at the risk of missing any true events of relevance to this project.

Consideration was also given to high acceleration readings occurring prior to the change in ignition state, specifically examining peaks in pitch (gyro y) and up/down (acceleration y) acceleration occurring within five seconds of the ignition moving out of the "Run" position in the SHRP 2 NDS database. This approach did result in finding relevant inertial events involving severe road undulations (e.g., railroad crossing). Figure 77 illustrates the six available parameters of acceleration within the SHRP 2 NDS database.

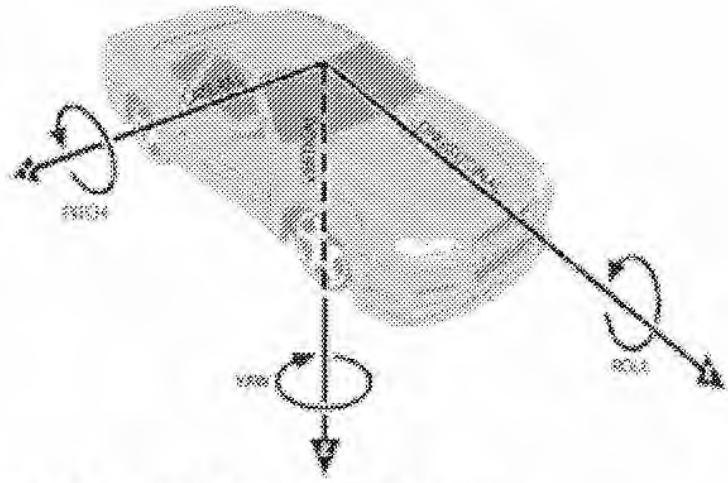


Figure 77. SHRP 2 acceleration diagram.

Queries within the SHRP 2 NDS database were limited to GM vehicles only, as listed in Table 3 and Table 4. A full-scale analysis of inertial events in the SHRP 2 NDS database exceeded the scope of this effort, thus a review of all flagged events based on the query output was not possible. As such, cases found and discussed within this section are based on an incomplete review of all possible returned events. However, targeted events were more likely to reveal events of interest, so priority was given for flagged events that met these criteria.

As of the writing of this report, five cases of inertial events were observed in the SHRP 2 NDS database. As stated, any purposeful ignition-state change made by the driver while the vehicle was in motion was not included in the database review for this project. This includes cases during which drivers turned the car off and even removed the key during a parking maneuver, a behavior that was observed as routine for at least two drivers. However, cases of ignition-state changes that were not purposefully made by the drivers were reviewed by the VTTI project team for a possible inertial event. The five cases are discussed below, with corresponding screenshots from the SHRP 2 NDS video data. It should be noted that, for all SHRP 2 NDS screenshots provided herein, the image quality is of a higher resolution during video analysis. It should also be noted that all participants of VTTI naturalistic driving studies are ensured human subjects protection through an Institutional Review Board process and data-sharing agreements. Such protections limit the amount of visuals that can be provided publicly. Therefore, any identifying data for the driver (e.g., a face view) must be excluded from this report, and no video can be embedded. It should be noted that the VTTI DAS is programmed to turn off within approximately five seconds after the ignition moves out of the "Run" position.

GM Inertial Case #1: 2005 Chevrolet Cobalt

In this example (Figure 78), the driver of a 2005 Chevrolet Cobalt is making a right-hand turn into the parking lot of a fast food restaurant. The parking lot is elevated relative to the roadway, and making the right turn into the entrance exerts visible acceleration spikes across the available parameters, including lateral, up/down, and pitch forces (Figure 79). Video review reveals a significant amount of swinging force centered on the key ring items associated with this maneuver. The vehicle leaves the “Run” position, at which point the driver was able to quickly restart the vehicle and continue. This was the first of two inertial-related events found for this particular driver/vehicle. Although not an extreme example, there are a number of items attached to the key chain that certainly play a role in the ability of the ignition key to rotate.

Figure 78. SHRP 2 Chevrolet Cobalt inertial case.

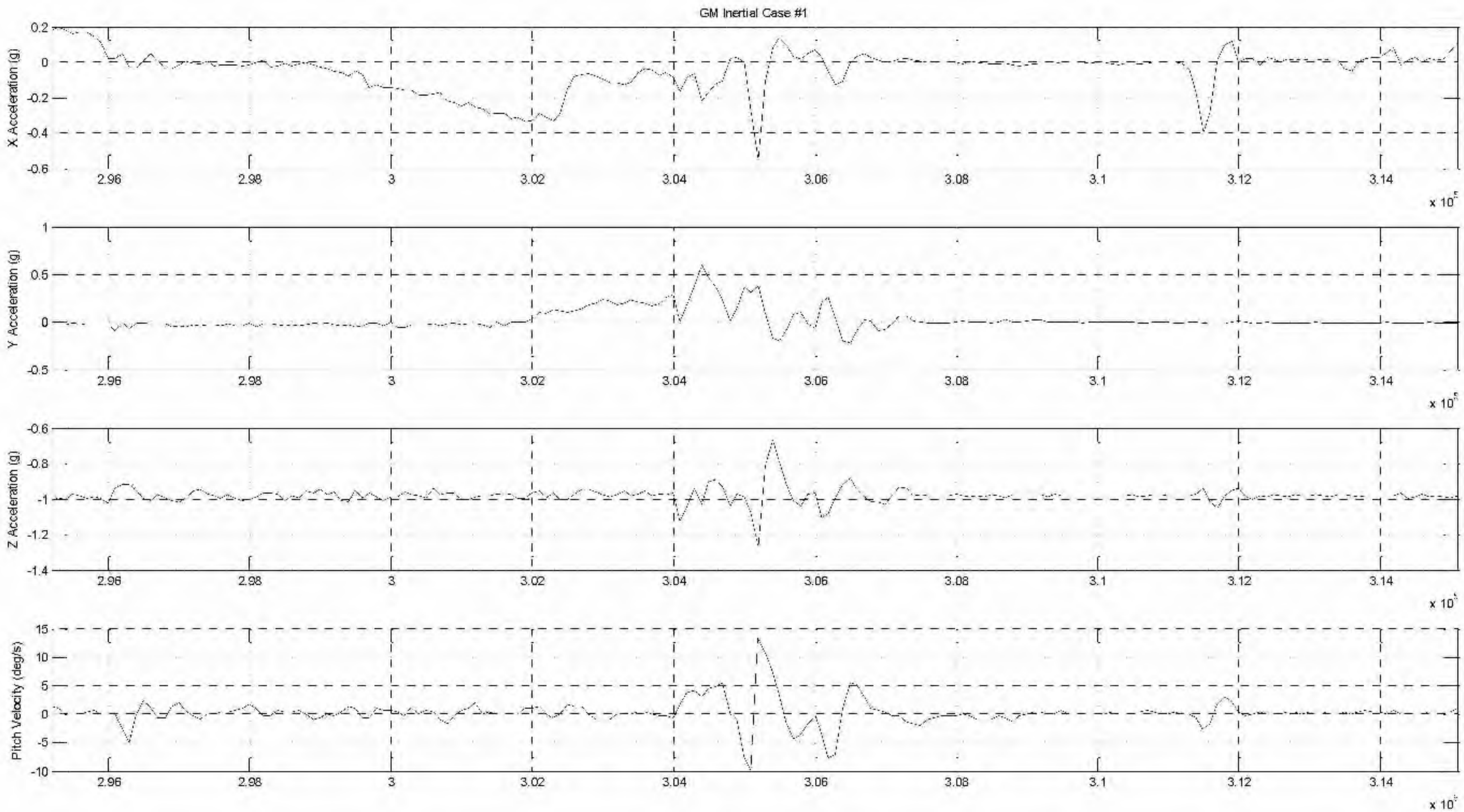


Figure 79. SHRP 2 Chevrolet Cobalt inertial data.

GM Inertial Case #2: 2005 Chevrolet Cobalt

In the second example of the 2005 Chevrolet Cobalt (Figure 80), the same driver experiences an inertial event, albeit one that is unrelated to acceleration forces relative to the driving task. In this trip file, the driver is observed pulling out of a parking space. While exiting and beginning to drive away, the driver adjusts the steering column. The steering column is observed dropping to its lowest point, and the force exerted by this movement is enough to rotate the ignition key out of the "Run" position. The inertial data for this event are shown in Figure 81. However, since the inertial input is provided by the driver moving the steering wheel, no real inertial acceleration is measured within the SHRP 2 NDS database. In this case, the trip file ends as the driver appears to recognize that the vehicle moved out of the "Run" position and prepares to re-start.

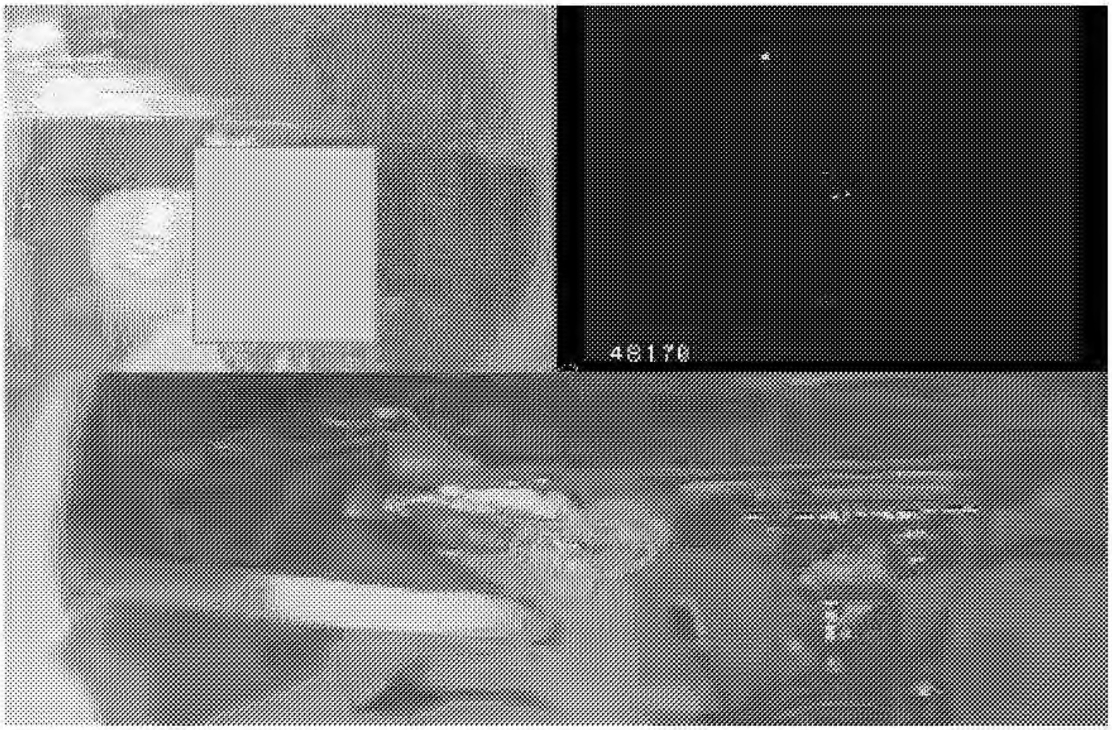


Figure 80. SHRP 2 Chevrolet Cobalt inertial case.

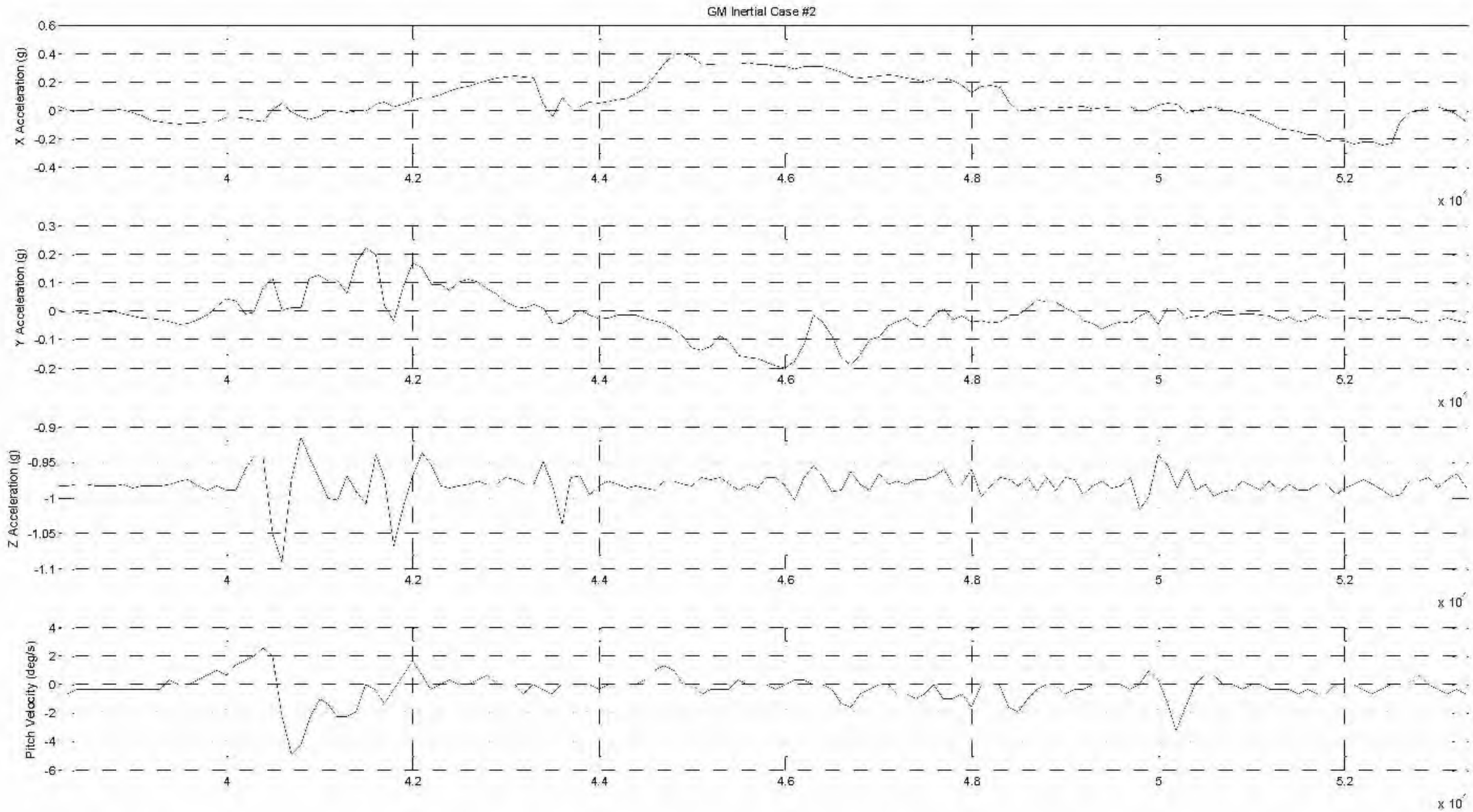


Figure 81. SHRP 2 Chevrolet Cobalt inertial data.

GM Inertial Case #3: 2002 Chevrolet Impala

In this particular example (Figure 82), the driver of a 2002 Chevrolet Impala is exiting a two-lane road, slowing down to make a right turn. While turning, the driver appears to cut the turn slightly, catching the area between where the pavement and the roads meet. During this maneuver, the key chain is visibly swinging, and it appears that there is a small pocket purse and a number of other items attached to the ignition key. During this event, acceleration parameters are noticeable primarily in the lateral, longitudinal, and pitch directions (Figure 83). The driver appears to recognize that the vehicle has moved out of the “Run” position, but the trip file ends before the driver’s attempt to re-start the vehicle is observed. This same driver experiences two other inertial events (Cases #4 and 5) in the same 2002 Chevrolet Impala, as based on review of flagged events to date.

Figure 82. Chevrolet Impala inertial event.

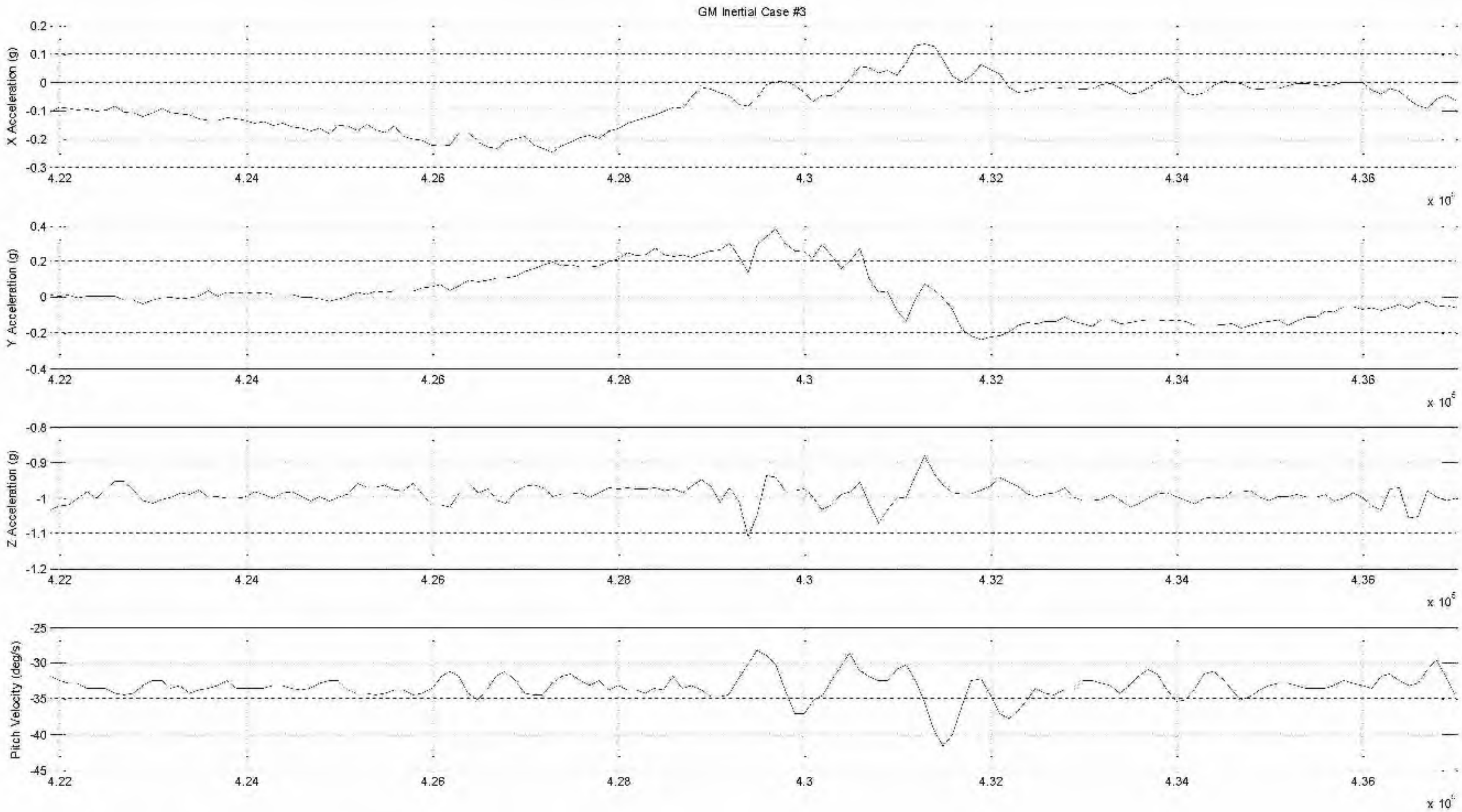


Figure 83. SHRP 2 Chevrolet Impala inertial data.

GM Inertial Case #4: 2002 Chevrolet Impala

In this case (Figure 84), the same driver of the 2002 Chevrolet Impala mentioned during Case #3 approaches a slightly elevated railroad crossing. The driver does slow down but is still traveling approximately 23 mph while cresting the crossing. Acceleration spikes are observed within the longitudinal, up/down, and pitch parameters (Figure 85). The driver appears to recognize that the vehicle has moved out of the "Run" position, but there is no observed attempt to re-start prior to the trip file ending.

Figure 84. SHRP 2 Chevrolet Impala inertial event.

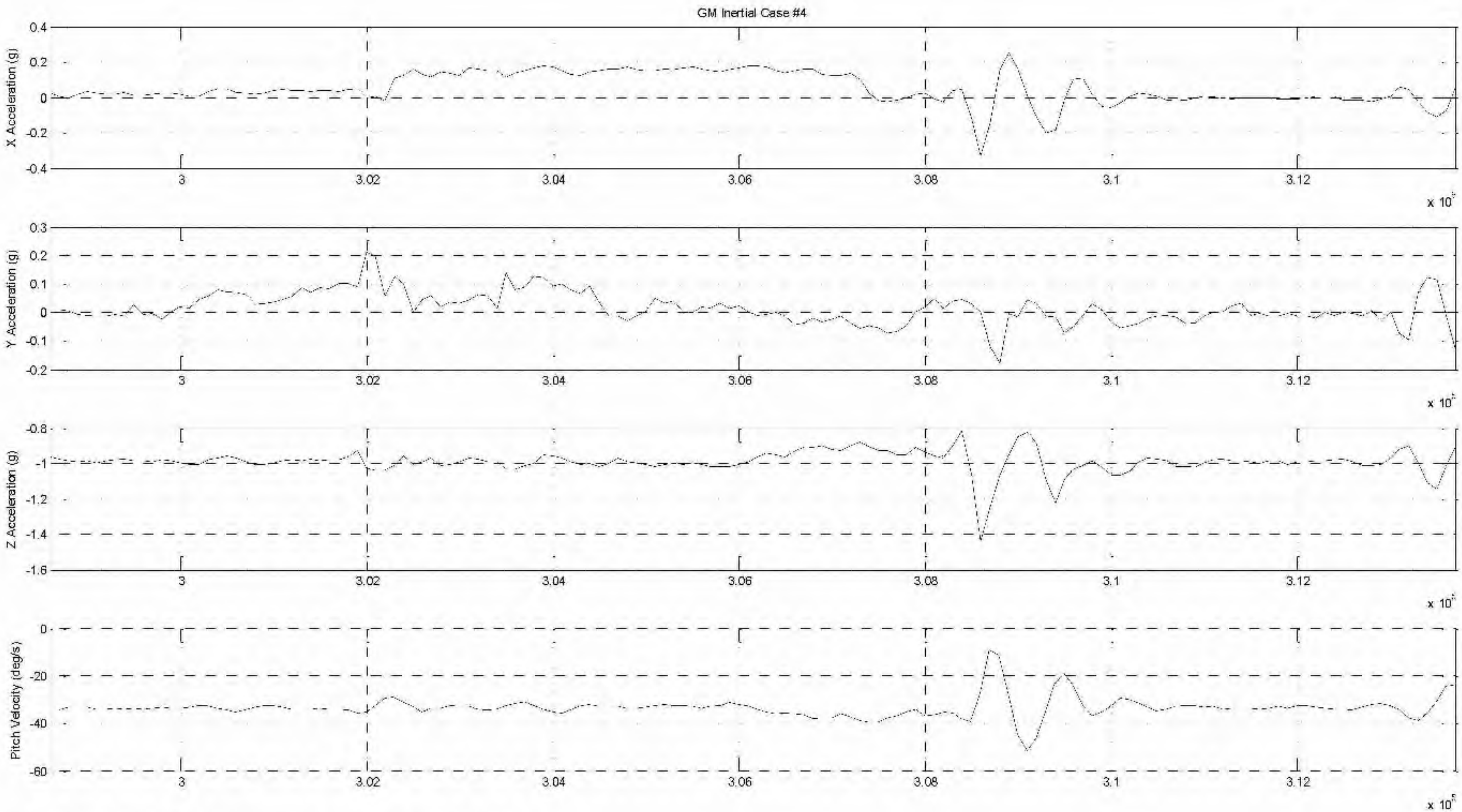


Figure 85. SHRP 2 Chevrolet Impala inertial data.

GM Inertial Case #5: 2002 Chevrolet Impala

In this inertial case (Figure 86), the same driver of the 2002 Chevrolet Impala is approaching a stop sign on a two-lane road. During her approach, the driver drives over a dip in the roadway, causing noticeable spikes in the longitudinal and pitch acceleration parameters (Figure 87). The vehicle immediately moves out of the “Run” position, but the trip file ends before any recognition by the driver is observed. This is the third event experienced by this particular driver based on review of SHRP 2 NDS events to date.

Figure 86. SHRP 2 Chevrolet Impala inertial event.

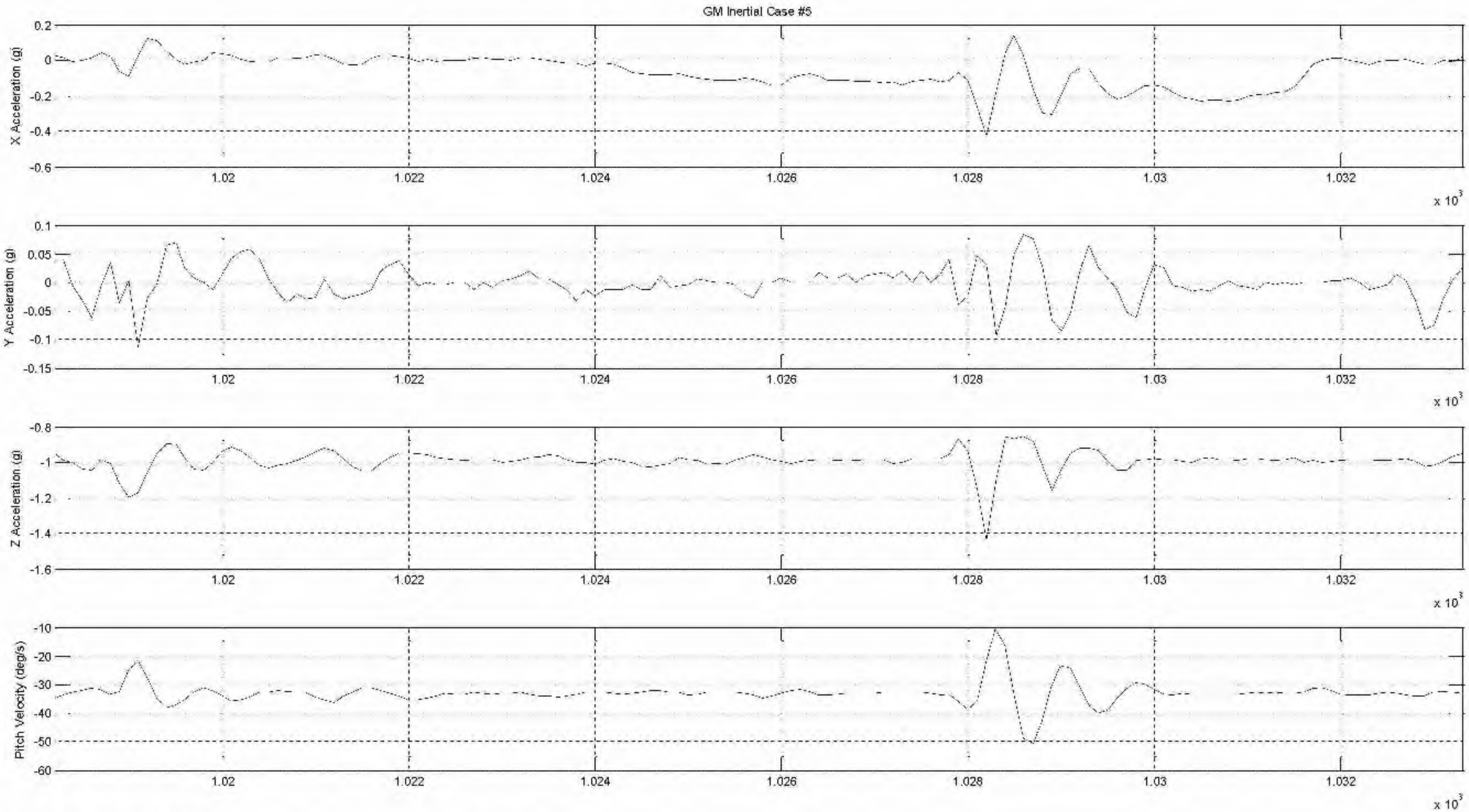


Figure 87. SHRP 2 Chevrolet Impala inertial data.

ASSESSING THE GM KNEE-KEY TEST

Overview

The ability of a driver to manipulate the ignition state of a vehicle with his/her knee during normal driving, thus moving the ignition key out of the "Run" position, is a safety-critical issue tied to many of the recalled GM vehicles. There are several variables that may interact, thus creating an opportunity for knee-key contact. These variables include: the layout of the driver's interior space, driver size, driving position, key angle in the "Run" position, and key size. Moreover, knee-key potential is not simply limited to the torque of the ignition switch itself. That is, a driver's knee is easily capable of producing forces high enough to overcome the torque required to move the ignition key out of the "Run" position. The VTTI project team confirmed via firsthand experience that ignition keys in the "Run" position can be easily manipulated by a driver's knee and moved to the "Accessory" position even in cars equipped with ignition switches with a greater torque than the industry average (e.g., approximately 22 Ncm, per a discussion with GM engineers), if the aforementioned variables combine to create a potential knee-key interaction.

As such, knee key is a difficult issue to capture and address considering the wide-ranging variability associated with driver size, desired positioning behind the wheel, the layout of the vehicular interior, the key angle, and the key size. Through the use of anthropometric data, automotive companies such as GM could easily expand current modeling practices for interior space design to include a predictive model that will aid in efficiently identifying the potential for knee-key interactions across the driving population.

This section provides a summary of GM's current approach towards evaluating the potential for knee-key interaction in GM vehicles and the existing state of the automotive industry with respect to knee-key issues. Five factors that can contribute to knee-key potential are then discussed in greater detail: 1) Anthropometric considerations; 2) In-vehicle adjustability range; 3) Key angle in the "Run" position; 4) Spatial relationship of the ignition switch; and 5) Key size. The VTTI project team then discusses instances of real-world, knee-key cases observed within the SHRP 2 NDS database.

Current GM Approach

Based on the test methodology observed during the VTTI project team's visit to the GM MPG, GM currently assesses the risk of knee key through targeted objective and subjective evaluations. Vehicles used for GM testing are prioritized and selected based on consumer complaints and their relationship to other vehicles with shared design components (i.e., platform-sharing vehicles) impacted by the ignition switch recall. Consumer complaints are monitored and collected across several sources, including the NHTSA "file a complaint" resource called SaferCar (www.safercar.gov), input from the GM dealer network, and direct communication with consumers. A database search of

SaferCar for knee-key related incidents pertaining to GM vehicles revealed complaints associated with Chevrolet Cobalts and HHRs (Table 7). It is worth noting, and not entirely unexpected, that four of the complaints were filed following the initial GM ignition switch recall during February 2014 (GM, 2014b), citing incidents occurring prior to the file date, including one referencing an incident occurring seven years prior to the file date.

Table 7. Knee-key Complaints for GM Vehicles, verbatim from www.safercar.gov.

Year	Make	Model	Complaint File Date	Incident Date	NHTSA ID Number	Complaint
2005	Chevrolet	Cobalt	July 8, 2005	July 1, 2005	10129121	"When the mechanics knee hit the bottom of the [FOB] it caused the ignition switch to shut off."
2005	Chevrolet	Cobalt	December 23, 2005	December 15, 2005	1014959	"On three occasions simply brushing the key chain with my leg was enough to turn the car off causing loss of power to the car."
2006	Chevrolet	Cobalt	April 9, 2014	February 22, 2014	10578779	"Driving down hwy. Knee bumped keys in ignition and the car shut off"
2007	Chevrolet	Cobalt	May 4, 2014	July 1, 2012	10586472	"Then, I was on the freeway on my way to work in 2013 and my knee bumped my key ring and they fell to the floor. I could not slow down or switch lanes.
2008	Chevrolet	Cobalt	March 3, 2014	May 2, 2013	10566822	"My leg accidentally bumped the keychain 3 3/8 inches long (only one key on it, the ignition key) while I was driving, and the car shut off."

2006	Chevrolet	HHR	April 24, 2014	January 1, 2007	10584765	"I was told that I was too short, fat, and my knee was knocking the key out of the ignition. My key never fell out of the ignition, but the car did shut off, losing control of all electrical systems while at 70+ mph."
2010	Chevrolet	HHR	February 26, 2014	February 26, 2014	10565981	"The contact stated while at a traffic light, she accidentally brushed the key against her leg causing the vehicle to stall."

GM currently uses available staff they claim represent a 5th percentile female and 50th and 99th percentile males in terms of height during its examination of knee-key potential. The selected individuals are asked to adjust the driver's seat and steering column to their normal driving positions. At this point, the percentile representatives attempt to turn the ignition key from the "Run" to "Accessory" position with their knees, rating the force required to do so on a scale of easy, medium, or difficult. If these percentile representatives can turn the key, they are asked to rate if such manipulation was achievable within a normal driving movement or one that was deliberate and beyond what should normally occur during routine driving (abnormal). Figure 88 illustrates the difference between normal and abnormal driving positions. As a final step during the knee-key evaluation, GM engineers measure the shortest straight-line distance from the driver's knee to the bottom of the key and key fob, where applicable.

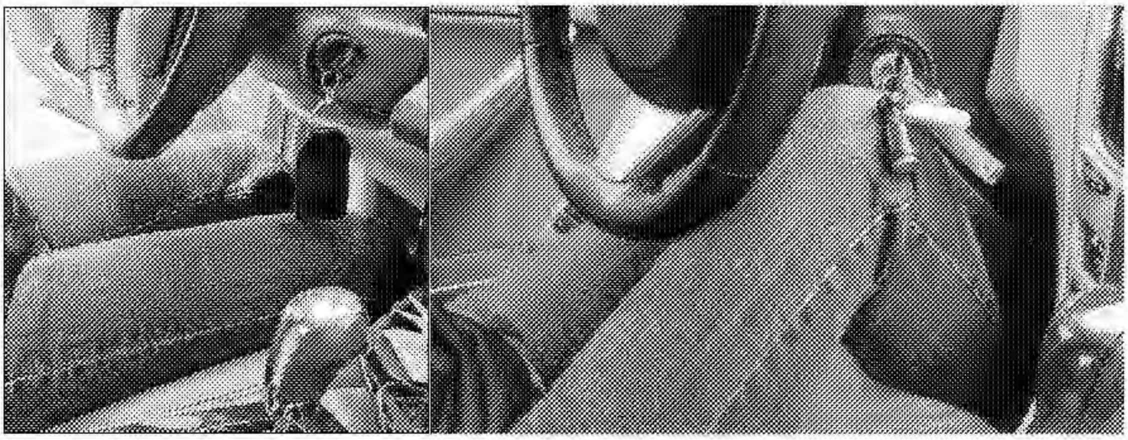


Figure 88. Normal (left) vs. abnormal (right) driving positions (photos courtesy of GM).

Measurements are also recorded by GM that pertain to key angles across the four typical positions within an ignition switch: "Off," "Accessory," "Run," and "Crank." Key angle is a contributing factor directly impacting the driver's ease and ability to manipulate the ignition state of a vehicle, as discussed later within this report. Key angles are recorded in degrees, with 12:00 representing 0, as illustrated in Figure 89.

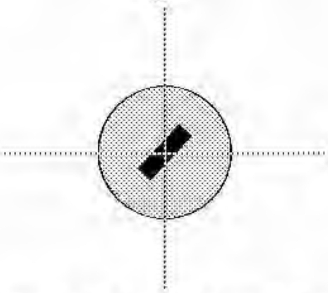


Figure 89. Key angle representation.

Test Results

GM provided sample outputs from its knee-key evaluations for review by the VTTI project team; summarized findings thereof are provided within Table 8. The sample output included five makes and a combined eight models, with a bias towards a dash-mounted ignition switch (Figure 90) versus one located on the steering column (Figure 91). Immediate observations reveal that knee key was not an issue for the representative 5th percentile female within this vehicle set. However, knee-key issues were present for the 50th and 99th percentile males across approximately half of the sample. All vehicles in which at least one percentile representative provided an ignition key rotation rating of easy (n=10) have been included under a 2014 recall linked to the ignition switch (GM, 2014b). Notably, eight of the included vehicles demonstrated difficult or impossible ratings across all three percentile representatives during GM knee-key testing. Six of these eight vehicles were recalled under replacement of the ignition key from a slot to a hole design in the key head, except for two cases. Despite the 2002 Chevrolet Malibu and 2003 Oldsmobile Alero scoring well in the subjective assessment during GM's knee-key testing, both are under a separate recall for "unintended key rotation" (GM, 2014b), suggesting there were other criteria factored into this decision made by GM to recall these vehicles.

One important observation made in reviewing the GM data was a note indicating that a second 99th percentile male sample found the ignition key in a 2010 Chevrolet Impala easy to manipulate, albeit in an abnormal driving position. This assessment is inconsistent with the primary 99th percentile representative, who indicated that the ignition key in this same vehicle was impossible to manipulate. This observation validates the variation of a driver's knee-key possibility due to seated position and/or driving style across multiple samples that are, by height and weight standards, included within the same overall percentile. That is, drivers of comparable height and weight may have vastly different driving styles that affect their ability to experience a knee-key

issue. Accounting for this variability is an important consideration moving forward and will be discussed in greater detail within this report.

Table 8. Provided Sample of Knee-key Test Results for GM Vehicles.

Year	Make	Model	Ignition Swtich Location	Key Angle (Run)	Ign Switch Torque (Ncm)	System Torque (Ncm)	5th % Female		50th % Male		99th % Male		Recalled?
							Difficulty	Position	Difficulty	Position	Difficulty	Position	
2006	Buick	LaCrosse	Dash	55	12.6	17.0	Difficult	Abnormal	Impossible		Impossible		Yes
2006	Buick	Lucerne	Steering Column	55	13.0	17.8	Impossible		Impossible		Impossible		Yes
2004	Cadillac	DTS*	Steering Column	23	11.8	15.0	Impossible		Impossible		Impossible		Yes
2007	Cadillac	DTS	Steering Column	53	11.1	16.8	Impossible		Impossible		Impossible		Yes
2000	Chevrolet	Impala	Dash	61	10.2	17.6	Impossible		Easy	Abnormal	Easy	Abnormal	Yes
2003	Chevrolet	Impala	Dash	60	8.9	13.3	Difficult	.	Medium	Abnormal	Easy	Abnormal	Yes
2004	Chevrolet	Impala	Dash	60	10.4	11.2	Difficult	Abnormal	Easy	Abnormal	Easy	Abnormal	Yes
2007	Chevrolet	Impala	Steering Column	30	12.4	18.0; 15.9	Difficult	.	Impossible		Impossible		Yes
2010	Chevrolet	Impala	Steering Column	50	10.8	21.9	Difficult	Abnormal	Impossible		Impossible***		Yes
2002	Chevrolet	Malibu	Dash	.	10.7; 9.6	15.0; 12.2	Impossible		Impossible		Impossible		Yes
2005	Chevrolet	Malibu Classic	Dash	60	14.1	16.1	Difficult	Abnormal	Impossible		Medium	Abnormal	Yes
2006	Chevrolet	Malibu Classic**	Dash	67	13.7	15.6	Difficult	Abnormal	Medium	Abnormal	Medium	Abnormal	No
1999	Oldsmobile	Alero	Dash	59	9.9	14.6	Impossible		Easy	Abnormal	Easy	Abnormal	Yes
2003	Oldsmobile	Alero	Dash	.	9.3	11.2	Difficult	.	Impossible		Impossible		Yes
1999	Pontiac	Grand Am	Dash	59	9.7	16.9	Difficult	Abnormal	Easy	Abnormal	Easy	Abnormal	Yes
2001	Pontiac	Grand Am	Dash	62	8.7	11.9	Difficult	Abnormal	Easy	Abnormal	Easy	Abnormal	Yes
2002	Pontiac	Grand Am	Dash	67	11.5	14.9	Difficult	Abnormal	Easy	Abnormal	Easy	Abnormal	Yes
2005	Pontiac	Grand Am	Dash	60	13.4	15.3	Difficult	Abnormal	.	.	Easy	Abnormal	Yes
2004	Pontiac	Grand Prix	Dash	55	8.6	10.5	Impossible		Easy	Abnormal	Easy	Abnormal	Yes
2008	Pontiac	Grand Prix	Dash	59	16.3	18.1	Difficult	Abnormal	Easy	Abnormal	Easy	Abnormal	Yes

** Deville*

*** Tests listed a 'Classic' but that trim was only available in 2004-2005; VTTI assumes this was a standard 2006 Malibu*

**** 2nd 99th sample indicated Easy/Abnormal*

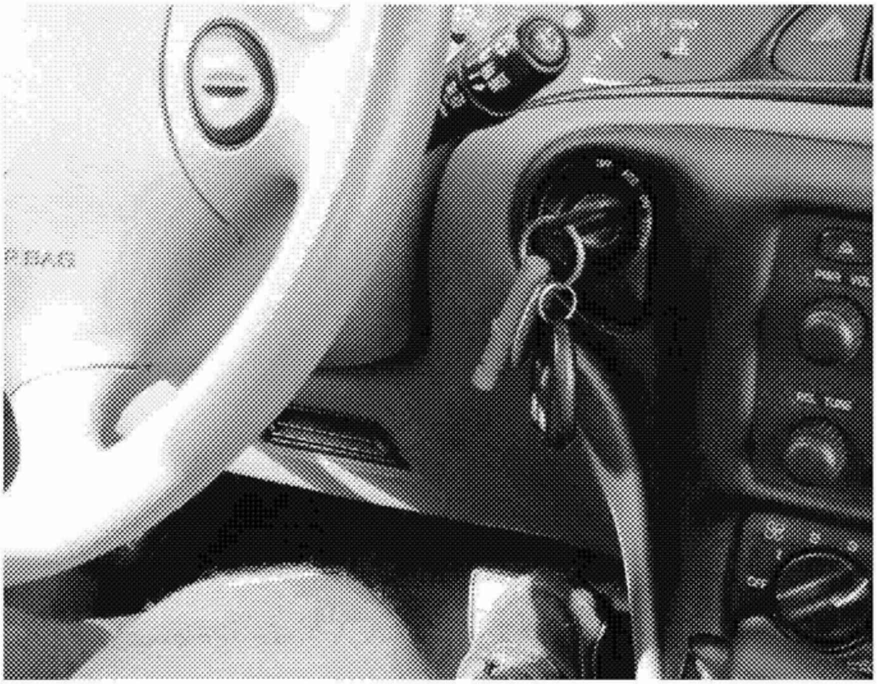


Figure 90. Example of dash-mounted ignition switch (2003 Chevrolet Malibu).

Figure 91. Example of steering wheel-mounted ignition switch (2010 Chevrolet Impala).

Industry-wide Considerations

Based on exposure to non-GM vehicles during its MPG visit, it was apparent to the VTTI project team that the potential for knee-key interactions is one that impacts the automotive industry beyond GM. Further confirmation was provided during the writing of this report when Chrysler issued a recall on July 22, 2014, impacting nearly 800,000 Jeep Commanders and Grand Cherokees due to the fact that "an outside force, usually attributed to contact with the driver's knee, may move ignition keys from the 'on' position" (Chrysler, 2014). Therefore, the VTTI project team determined that it was important to test non-GM vehicles during this project as a means of benchmarking industry standards regarding knee-key issues. The VTTI project team requested that six manufacturers be tested across eight non-GM vehicle models, including Chrysler, Ford, Honda, Hyundai, Toyota, and Volkswagen (Table 9). For consistency in use of percentile representatives, the VTTI project team requested that GM perform this evaluation with the same percentile representatives used to assess the GM vehicle samples. As Table 9 illustrates, outside of the Ford F-150, each percentile representative claimed the ignition key was easy to manipulate with his/her knee across a mix of normal and abnormal driving positions within non-GM vehicles.

Table 9. Requested Sample of Knee-key Test Results for Non-GM Vehicles.

Year	Make	Model	Ignition Switch Location	Key Angle (Run)	Ign Switch Torque (Ncm)	System Torque (Ncm)	5th % Female		50th % Male		99th % Male	
							Difficulty	Position	Difficulty	Position	Difficulty	Position
2013	Ford	F-150	Steering Column	30	.	17.5	Difficult	Abnormal	Difficult	Abnormal	Difficult	Abnormal
2012	Honda	Civic	Steering Column	25	.	16.2	Easy	Abnormal	Easy	Abnormal	Easy	Abnormal
2012	VW	Passat	Steering Column	0	.	37.5	[illegible]	[illegible]	Easy	Abnormal	[illegible]	[illegible]
2012	Ford	Focus	Steering Column	30	.	18	Easy	Abnormal	Easy	Abnormal	Easy	Abnormal
2012	Honda	CR-V	Steering Column	35	.	17.8	Easy	Abnormal	Easy	Abnormal	Easy	Abnormal
2013	Ram	1500	Dash	5	.	20.2	[illegible]	[illegible]	Easy	Abnormal	Easy	Abnormal
2013	Toyota	RAV4	Steering Column	42	.	22.9	Easy	Abnormal	Easy	Abnormal	Easy	Abnormal
2013	Hyundai	SantaFe	Steering Column	-7	.	21.6	Easy	Abnormal	Easy	Abnormal	[illegible]	[illegible]

Another important observation relates to the torque measurements (i.e., the required applied force to rotate the key in the ignition switch). Compared to the sample of GM vehicles (Table 8), there is a greater range of torque values among non-GM vehicles, from a low of 16.2 Ncm up to 37.5 Ncm. As expected, results reveal that the designed torque settings are easily overcome by the force applied by a driver's knee. Although low-torque ignition switches may be more susceptible to knee-key interactions and could more easily experience inertial effects, knee key is an issue that increased torque alone will not address.

The VTTI project team searched the NHTSA SaferCar database to determine if any consumer complaints were logged for knee-key instances associated with non-GM vehicles. Keywords used to search the database included: "leg," "knee," "key," and "ignition off." Specific examples were uncovered pertaining to Chrysler vehicles, particularly the 2011 Dodge Ram 1500 and three model years (2005, 2006, and 2008) of the Jeep Grand Cherokee (Table 10). Again, it is unsurprising that the file dates for these complaints occurred following the initial GM recalls.

Table 10. Consumer Knee-key Complaints for Non-GM Vehicles, verbatim from www.safercar.gov.

Year	Make	Model	Complaint File Date	Incident Date	NHTSA ID Number	Complaint
2011	Ram	1500	June 14, 2012	June 25, 2011	10461764	"Right knee bumps the large key turning it, and shutting off the engine, making it hard to control. This has happened several times usually while cornering or slowing for a corner."
2006	Jeep	Grand Cherokee	July 24, 2014	July 9, 2014	10616124	"My knee must have bumped the keychain and apparently it turned the ignition off."
2005	Jeep	Grand Cherokee	July 23, 2014	September 1, 2005	10615555	"My knee hit the ignition switch while I was driving, which turned the vehicle 'off' at 65mph on the highway. The brakes and the steering lost power. This is happened about 10 times overall."
2005	Jeep	Grand Cherokee	July 4, 2014	July 1, 2010	10608196	"The problem seems to be caused if I bump the key ring with my knee or I hit a small bump in the road." "As of late, this seems to happen about every time I drive the car."

2006	Jeep	Grand Cherokee	July 2, 2014	April 10, 2007	10607785	"While driving various speeds on a bumpy road, the vehicle stalled when the contact's knee struck the ignition key."
2005	Jeep	Grand Cherokee	June 28, 2014	November 5, 2008	10606610	"I attributed the problem to the location of the ignition switch which makes it almost impossible not to bump into the key with your right knee anytime you're traveling long distances and wind up moving your feet around just to stretch them."
2008	Jeep	Grand Cherokee	June 23, 2014	April 10, 2010	10605421	"This also occurs sometimes when you go over a bump or if your knee touches the key ring."
2005	Jeep	Grand Cherokee	June 23, 2014	June 4, 2013	10605209	"While driving the vehicle, the contact's knee bumped the ignition key and the vehicle stalled. The failure recurred (sic) four times within eight months."

Knee-key Factors

The following sections discuss factors identified as contributors to the knee-key problem, with the understanding that the potential for a knee-key scenario is typically the result of interactions between two or more of these factors. These factors are discussed relative to the current evaluation approach used by GM; current and future recommendations made by the VTTI project team are provided.

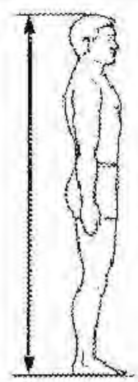
Anthropometric Considerations

Accounting for size variability within the driving population is a challenge but a critical consideration associated with the knee-key issue. Although general predictions of driving position can be inferred by body size, it is more than reasonable to conclude that variations between multiple samples within a single percentile could choose substantially different driving positions, especially considering the range of adjustability within today's vehicles. This variation was, in fact, observed within the sample data set provided by GM. Variability is further impacted when one considers that multiple samples within a single percentile (e.g., height) may have measureable differences across more specific anthropometric measures that impact driving positions, such as arm reach, foot-to-knee height, etc. Thus, it is important to examine knee-key potential using percentile representatives who demonstrate specific body measurements and not simply overall height.

As a starting point for anthropometric reference, available sources through which summary statistics are publicly available at no cost (e.g., Anthropometric Survey [ANSUR; Gordon et al., 1989], Civilian American and European Surface Anthropometry Resource Project [CAESAR; Harrison & Robinette, 2002]) suggest that the height and weight percentiles to consider in the GM knee-key evaluations are as follows (Table 11). ANSUR was an effort conducted in 1988 cataloging an extensive range of anthropometric measurements across almost 4,000 military personnel. However, CAESAR may be more appropriate for use in this project as it was conducted more recently and was not limited to military personnel. CAESAR encompassed a total of more than 2,400 and 2,000 civilians in the U.S. and Europe, respectively, between 1998 and 2000. Note that Table 11 includes CAESAR summary statistics limited to the U.S. sample.

Table 11. Height of Males and Females across 1st, 50th, and 99th Percentiles (Gordon et al., 1989; Harrison & Robinette, 2002).

Stature			
Gender	**Percentile**	**ANSUR**	**CAESAR**
Male	1st	63.10"	63.21"
	50th	69.09"	69.25"
	99th	75.14"	77.36"
Female	1st	58.39"	58.69"
	50th	64.06"	64.15"
	99th	70.09"	71.85"



Knee-key evaluations at GM should also examine the potential for ignition key contact and manipulation throughout a range of driving-related movements and positions,

including accelerator, brake, and "cruise" positions. GM has confirmed that it currently uses a range of driving movements and positions when testing for knee-key plausibility. However, it is recommended that GM include the following driving positions relative to the driver's knee placement, if the company is not doing so already:

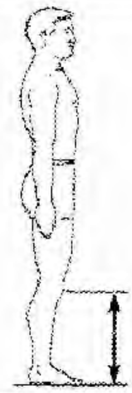
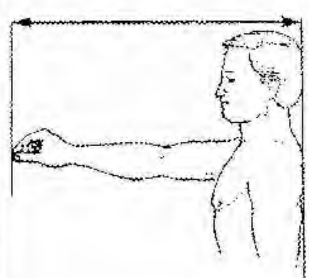
1. Foot on accelerator – place right foot flat on accelerator pedal
2. Foot on brakes – place right foot flat on brake pedal
3. Foot in "cruise" mode – place foot flat on floor, representing typical foot placement when cruise control is engaged. Available literature (McLaughlin, 1998) suggests that this is one position typically observed when the cruise control is engaged. This position is selected above others herein because it represents the worst-case scenario relative to possible knee-key interaction (i.e., such position forces the driver's knee upwards and closer to the typical ignition switch mounting locations).

It is equally important to examine knee-key potential during transitions between these driving positions, as contact may occur when the driver's foot moves from one location to another and back. In some cases, transitioning between these positions may not only cause the knee to strike the ignition key while in the "Run" position but will also create the potential for manipulation of the ignition state through a binding force applied to the key fob, if the latter is hanging on a key chain, for example. GM should continue to examine the ability of a driver's knee to manipulate the ignition key within abnormal driving positions as well, simply by testing the ability to cause rotation and noting the difficulty thereof. If manipulation is possible yet difficult in an abnormal driving position, such a scenario would suggest the likelihood of knee key occurring during normal driving is essentially nonexistent.

The existing approach GM is taking to test for knee key is certainly a useful first step in identifying anthropometric variations that are susceptible to such a scenario. Because of the safety impact, however, it is the immediate suggestion of the VTTI project team that GM expand its assessment of the driving population to include the 1st percentile female. It is also important that GM verify the percentile appropriateness of the chosen representatives using a recent anthropometric database (e.g., CAESAR).

GM should also consider conducting its knee-key tests with available staff who represent the breadth of percentiles specific to body measurements that have a more direct influence on seated position, as opposed to simply overall height. Specifically, these body measurements should include arm lengths associated with a driver's overall reach (fingertip to shoulder) and upper (knee to buttock) and lower leg (foot to knee) lengths. Table 12 illustrates specific body measurements GM should consider benchmarking for its percentile representatives as opposed to simply accounting for overall height (note that CAESAR references include the U.S. population data only).

Table 12. Specific Body Measurements of Males and Females across 1^{st}, 50^{th}, and 99^{th} Percentiles (Gordon et al., 1989; Harrison & Robinette, 2002).

Knee Height, Midpatella (ANSUR); Knee Height, Standing (CAESAR)				
Gender	**Percentile**	**ANSUR**	**CAESAR**	
Male	1^{st}	17.44"	16.84"	
	50^{th}	19.84"	19.35"	
	99^{th}	22.37"	22.33"	
Female	1^{st}	15.73"	15.32"	
	50^{th}	18.03"	17.45"	
	99^{th}	20.58"	20.09"	
Buttock-Knee Length				
Gender	**Percentile**	**ANSUR**	**CAESAR**	
Male	1^{st}	21.68"	21.41"	
	50^{th}	24.23"	24.03"	
	99^{th}	27.04"	27.86"	
Female	1^{st}	20.54"	19.98"	
	50^{th}	23.14"	22.97"	
	99^{th}	25.99"	27.35"	
Thumb Tip Reach				
Gender	**Percentile**	**ANSUR**	**CAESAR**	
Male	1^{st}	28.34"	28.22"	
	50^{th}	31.49"	31.67"	
	99^{th}	35.31"	35.92"	
Female	1^{st}	25.91"	25.60"	
	50^{th}	28.88"	28.96"	
	99^{th}	32.44"	33.02"	

Range of In-vehicle Adjustability

As discussed in relation to the anthropometric considerations, the range of seating and steering column adjustability in today's vehicles introduces additional variability in

examining knee-key potential across the driving population. These vehicles offer wide-ranging adjustability within the driver's space, resulting in an exponential number of seated positions. In almost all cases, seat pans can be adjusted forward and back, as well as up and down. Many vehicles also offer the ability to angle the seat by adjusting the front so the rear of the seat pan is closer to the horizontal plane. Seat backs can recline, and steering columns often offer telescoping in addition to up/down adjustability. Pedals that offer adjustability are also becoming more common in today's automotive marketplace. An example of the range of driver position adjustability is provided in Figure 92, based on a 2014 Chevrolet Silverado.

Adjustment Ranges

- Recline: Δ 55°
- Seat Height: Δ 70mm
- Seat Longitudinal: Δ 320mm
- Cushion Tilt: Δ15°
- Steering Wheel Telescope: Δ 45mm
- Steering Wheel Tilt: Δ 25°
- Adjustable Pedals: Δ 105mm

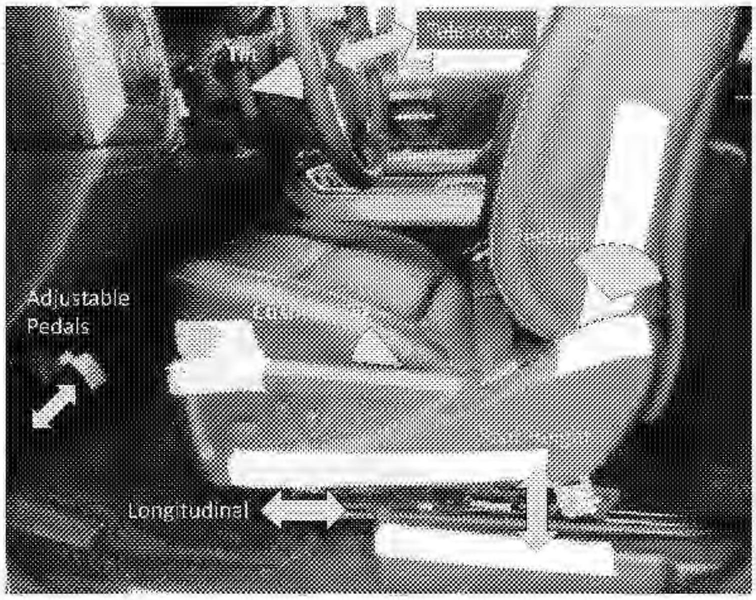


Figure 92. Example of range of in-vehicle adjustability (2014 Chevrolet Silverado). Photo and specifications courtesy of GM.

Current knee-key tests conducted by GM are centered upon the personal driving position of the primary percentile representatives of the 5th female and 50th and 99th males, which is limiting. Therefore, consideration should be given to examining the potential for knee key within other reasonably likely driving positions for similarly statured persons.

Recommendations that may be applied to the current knee-key testing approach used by GM include testing more than one representative per percentile classification. If testing continues using a single percentile representative, it is suggested that GM instruct such representatives to evaluate the potential for knee-key interaction across other possible seated positions.

Key Angle in the "Run" Position

The ignition key angle in the "Run" position is another critical factor to consider for knee-key plausibility. However, this factor is one that is heavily dependent upon others, likely more so than any other factor contributing to potential ignition key contact. An optimal

ignition key angle target should minimize the ability of a driver's knee to apply enough pressure to the ignition key face, or the side with the largest surface area. It is difficult to determine a clear pattern of appropriate ignition key angle in the "Run" position based solely on the sample results provided by GM (Table 8 and Table 9), particularly due to such uncontrolled factors as the mix of dash- versus steering column-mounted ignition switches. Ignition key angle is certainly impacted by the mounting location of the ignition switch (i.e., steering column versus dash) but is also relative to the floor and other interior points. This suggests that the optimal angle will likely vary by vehicle, even if other constraints are kept constant. What should be avoided, of course, is the primary example of the fifth-generation Chevrolet Camaro key, where a combination of ignition key size and angle in the "Run" position allows for easy manipulation of the ignition state by the driver's knee (Figure 93).

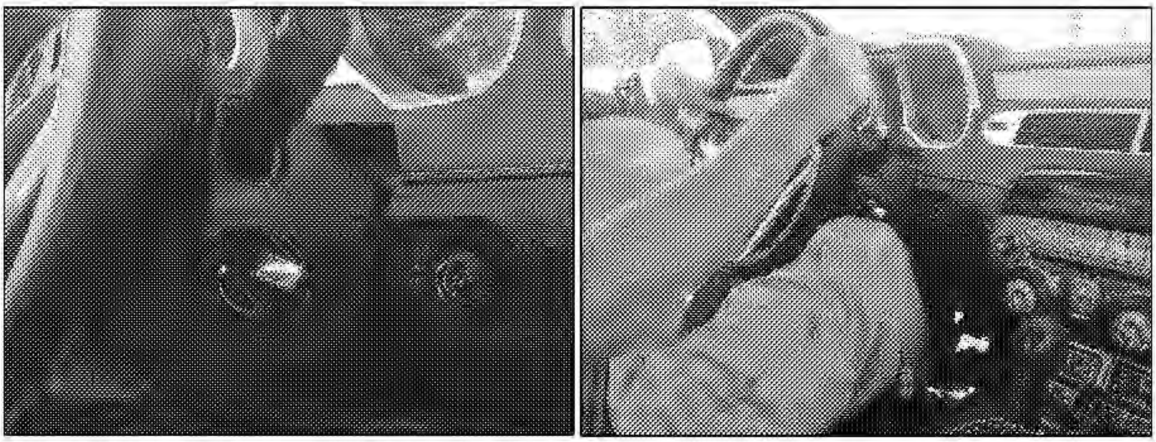


Figure 93. 2012 Chevrolet Camaro key angle.

Ideally, the ignition key face, or the side of the ignition key with the largest surface area, should be as perpendicular as possible to the driver's knee during normal driving positions, likely somewhere in the 45-degree range. However, this is imperfect logic due to the impact of other factors identified and discussed within this report. As such, the ignition key angle is not a factor that can be easily standardized, but it should be examined for appropriateness during the design and development process associated with new vehicles. It is important to recognize that considerations also vary by the mounting placement of the ignition switch. A steering column-mounted ignition switch would typically be susceptible to upward and forward pressure applied by the driver's knee, whereas a dash-mounted switch requires consideration of upward and side pressure applied by the driver's knee.

Ultimately, consideration of the ignition key angle will not provide a solution independently. That is, the ignition key angle should not be the sole consideration when designing to eliminate the potential for a knee-key scenario. As the VTTI project team was exposed to a variety of both GM and non-GM vehicles during its visit to GM MPG, a number of both types of vehicles proved easy to manipulate in relation to a knee-key issue, though often in abnormal driving positions. For example, the 2013 Toyota RAV-4 ignition key is at an estimated 45- to 50-degree angle in the "Run" position (42 degrees,

per GM measurements provided in Table 9). As Figure 94 shows, the key is relatively perpendicular to the driver's knee. This ignition key angle in the "Run" position appears appropriate in minimizing risk, but sufficient space between the ignition switch and the steering wheel does allow for a driver's knee to contact the ignition key face and apply direct pressure, thus causing rotation. This would, of course, be an abnormal position for the majority of the driving population, but consideration of other factors discussed in this report, in conjunction with the ignition key angle, can all but eliminate this risk entirely.

Figure 94. 2013 Toyota RAV-4 ignition key angle.

As discussed previously, the potential for a knee-key scenario also exists for dash-mounted locations. Similar logic in terms of an ignition key angle target within the 45-degree range applies to dash-mounted ignition switches (i.e., maintaining a perpendicular relationship between the driver's knee and the side of the ignition key with the lowest surface area). However, space considerations allowing for a driver's knee to apply force to the ignition key face will ultimately dictate the level of potential for a knee-key scenario. A primary example was the 2013 Dodge Ram 1500, as shown in Figure 95. The ignition key face (e.g., the largest surface area) in the "Run" position is parallel to the side of a driver's knee. This positioning, coupled with sufficient space between the steering column and the ignition switch, provides room for knee interference in a side-to-side movement.

Moving forward, the VTTI project team recommends that ignition key angle be assessed and evaluated for all unique vehicle models. Platform-sharing across vehicle models often spans a variety of vehicle types, and an appropriate ignition key angle in one vehicle may be susceptible in another vehicle, based primarily on the spatial layout of the vehicle interior and the relationship of the ignition switch location within that interior space.

Figure 95. 2013 Dodge Ram 1500 key angle.

Spatial Relationship of Ignition Switch

As mentioned in the previous section, if the area surrounding the ignition switch provides enough access for a driver to place his/her knee in contact with the ignition key, the potential for interference will exist, albeit often through positioning that is considered abnormal to the typical driving task. The classification of abnormal positioning still warrants consideration. Thus, taking steps to minimize the ability of a driver's knee to get in front of (steering column-mounted) or next to (dash-mounted) the ignition key is another important consideration. Of the GM and non-GM vehicles examined during the VTTI project team's visit to the GM MPG, one example of a column-mounted ignition switch that was subjectively assessed as near-impossible to manipulate was a 2013 Ford F-150. As shown in Figure 96, the ignition switch is both recessed within the steering column and positioned close to the rear of the steering wheel. This limited space pocket, combined with an appropriate ignition key angle, all but eliminates the ability of a driver's knee to contact the entirety of the ignition key face.

Figure 96. 2013 Ford F-150 ignition switch.

As a means of direct comparison, a 2014 Ford Expedition, which is essentially identical to the F-150 in terms of interior dimensions and layout respective to the driver, had a non-recessed ignition switch incorporated into the steering column (Figure 97). This single difference allows for much easier access and manipulation by a driver's knee, still considering that such a knee-key interaction would typically be achieved during an abnormal driving position. However, this example illustrates how two essentially identical vehicles could have very different knee-key potential as a result of a single design difference.

Figure 97. 2014 Ford Expedition ignition switch.

Initial perceptions made by the VTTI project team suggested that a dash-mounted ignition switch would, by location alone, be less susceptible to knee-key interactions. Of the vehicles to which the VTTI project team had access during its GM MPG visit, three vehicles had ignition switches located on the dashboard. This design approach was confirmed as a solution within two vehicles (2013 Ford Taurus and 2010 Nissan Frontier), but the third sample (2013 Dodge Ram 1500) revealed that knee-key potential was still present. The 2013 Ford Taurus (Figure 98) has an ignition switch located adjacent to the center stack. Although unconventional, this location essentially eliminates knee-key potential.

Figure 98. 2013 Ford Taurus ignition switch.

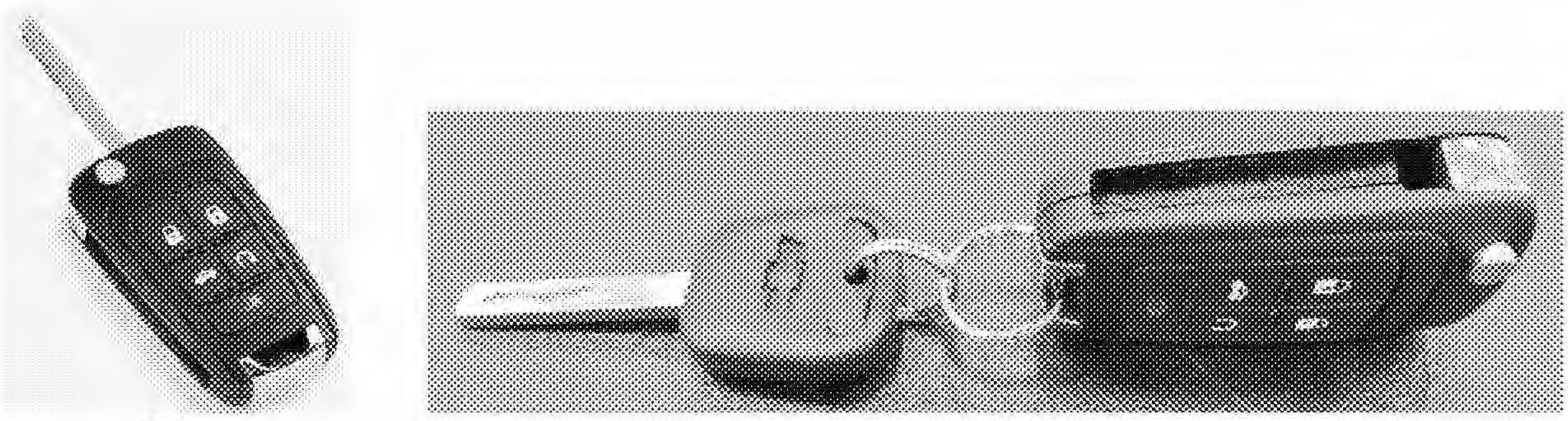
The 2010 Nissan Frontier incorporates a dash-mounted ignition switch between the steering column and center stack (Figure 99). The location of the switch is heavily recessed, and, when coupled with the narrow space relative to the steering column and ignition key angle in the "Run" position, this configuration all but eliminates the ability of a driver's knee to manipulate and/or contact the ignition key. Alternatively, the dash-mounted switch in the 2013 Dodge Ram 1500, which was discussed earlier within this report, is positioned within an area that allows for the driver's knee to get in between the ignition key and the steering column (Figure 95). This position, along with the ignition key angle, result in relatively easy manipulation of the ignition key while in the "Run" position.

The VTTI project team recommends that future ignition switches be recessed, regardless of mounting location. Additionally, space allowances should be carefully considered, and the areas that would allow for a driver's knee to apply pressure to the ignition key head should be minimized to the extent possible. This approach alone will reduce the potential for knee-key interactions.

Figure 99. 2010 Nissan Frontier ignition switch.

Key Size

Lastly, the size of the ignition key also plays a contributing role in a driver's ability to rotate the ignition key out of the "Run" position. Many manufacturers are offering integrated key fobs, creating a larger surface area with which the driver's knee can make contact. One primary example of a knee-key issue due to a larger surface area of the ignition key involves the recalled fifth-generation Chevrolet Camaro (i.e., model years 2010 to 2014). The original ignition key of the Camaro was an integrated fob with a switchblade key (Figure 100a). This key design, coupled with the location of the ignition switch and chosen ignition key angle in the recalled Camaros, resulted in an exceptionally easy ignition key that the driver could inadvertently contact and alter within normal driving positions, as was discussed earlier (Figure 93). The subsequent GM recall (GM, 2014b) will replace the switchblade key design of the Camaro with a traditional single key and separate key fob attached on a key ring (Figure 100b).



(a) (b)

Figure 100. Chevrolet Camaro keys, pre- (a) and post- (b) recall.

This key replacement limits the direct interaction between the driver's knee and the ignition key itself. However, care should be taken by GM in limiting the Camaro recall to this solution only, as the experience of the VTTI project team revealed that a driver's knee could still alter the ignition state if the fob became trapped between the driver's knee and the steering column in such a manner as to cause a binding force strong enough to pull the ignition key out of the "Run" position.

Predictive Model to Assess Knee-key Potential in Future Vehicles

It is the understanding of the VTTI project team that GM is in the process of developing a predictive model that will assess the potential for knee-key interactions across driver stature and driving position. This predictive model would objectively and efficiently measure the likelihood of knee-key interaction prior to physical in-vehicle evaluations performed using percentile representatives. This model will be incorporated into the driver diagrams currently used to design interior spaces for future GM vehicles. However, in the interest of providing a thorough systematic analysis within this report, the VTTI project team recommends that such a simulation model account for the factors cited and discussed above. Specifically, addressing the following issues will aid in the goal of ultimately eliminating, or designing out, future ignition switch issues.

The predictive model should accommodate input parameters associated with the following variables, as discussed within this report and summarized below:

1) Spatial characteristics of the driver's interior space
    a) Range of adjustability associated with the seat, steering column, and pedals
    b) Relationship of all fixed and adjustable points within the interior space
        i) Pedals to seat
        ii) Ignition switch to steering wheel, etc.
2) Anthropometric considerations using the most recent and representative anthropometric databases available (e.g., CAESAR); note that, although summary statistics are available within public reports, access to complete anthropometric databases can only be gained through a substantial fee
    a) 1st, 50th, and 99th percentile representations of male and female drivers for overall height
    b) Percentile representations associated with specific body measurements (e.g., lower and upper leg lengths, reach, etc.)
    c) Critical driving-related positions and transitions between:
        i) Accelerator
        ii) Brake
        iii) "Cruise-engaged"
3) Ignition key angle in the "Run" position
4) Ignition key head size

SHRP 2 Data Mining Task

As discussed previously, the VTTI SHRP 2 NDS database was searched, or mined, for cases during which the ignition state was unintentionally altered due to knee-key factors. To locate possible knee-key events in the database, the VTTI project team used a basic query that included an ignition state change out of the “Run” position occurring adjacent to a speed trace greater than or equal to 5 mph. Using this query approach, the VTTI project team discovered four knee-key events in the SHRP 2 NDS database, which comprises 519 GM vehicles (see Table 3 and Table 4).

It should be reiterated that a full-scale analysis of knee-key events in the SHRP 2 NDS database exceeded the scope of this effort, so a review of all flagged events based on the query output was not possible. As such, cases found and discussed within this report are based on an incomplete review of all possible returned events. However, the targeted events were more likely to reveal events of interest, so priority was given for flagged events that met these criteria.

As of the writing of this report, four cases of knee-key interactions were observed in the SHRP 2 NDS, with each case discussed in detail below. Atypical driving behavior was also observed; these cases are marked as “Other” below. As stated, any purposeful ignition-state change made by the driver while the vehicle was in motion was not included in the database review for this project. This includes cases during which drivers turned the car off and even removed the key during a parking maneuver, a behavior that was observed as routine for at least two drivers. However, cases of ignition-state changes that were not purposefully made by the drivers were reviewed by the VTTI project team for a possible knee-key scenario. The four knee-key and three non-knee-key/atypical (“Other”) cases are discussed below, with corresponding screenshots from the SHRP 2 NDS video data. It should be noted that, for all SHRP 2 NDS screenshots provided herein, the image quality is of a higher resolution during video analysis. It should also be noted that all participants of VTTI naturalistic driving studies are ensured human subjects protection through an Institutional Review Board process and data-sharing agreements. Such protections limit the amount of visuals that can be provided publicly. Therefore, any identifying data for the driver (e.g., a face view) must be excluded from this report, and no video can be embedded.

GM Case #1: 2005 Chevrolet Malibu

In this example, the driver of a 2005 Chevrolet Malibu is traveling along a two-lane road at approximately 62 mph. Figure 101 is a snapshot of the available in-vehicle view from the SHRP 2 NDS video; related scenario details are also provided. During review of the video, an interaction between the driver's leg and the ignition key is observed, with the driver's knee area pushing up on the ignition key in the dash-mounted ignition switch. After the ignition state leaves the "Run" position, the DAS turns off, and reaction by the driver is not observed. As stated previously, the VTTI DAS is programmed to turn off within approximately five seconds after the ignition state leaves the "Run" position.

Year	2005
Make	Chevrolet
Model	Malibu
Recalled Vehicle?	Yes
Gender	Male
Age	Younger
Ignition Switch	Dash
Speed at Ignition off	62mph
Belted?	Yes

Figure 101. SHRP 2 Chevrolet Malibu knee-key case.

GM Case #2: 2008 Saturn Astra

Another example of knee key within the SHRP 2 NDS database finds the driver of a 2008 Saturn Astra traveling down a multi-lane roadway at approximately 48 mph (Figure 102). The road itself is bumpy, and at one point the driver's knee applies a visible upward force on the ignition key. The driver appears to notice that the vehicle has left the "Run" position almost immediately, whereupon he first rotates the ignition key, shifts into neutral, then restarts quickly before continuing on his way. The driver is large in stature, and his knee is observed applying upward pressure to the side of the ignition key. Visibly, there are items attached to the ignition key, and, due to the driver's stature, these items are almost always resting on his upper leg, as observed during this case and other trips (Figure 103). This driver's knee typically appears very close to the ignition key, and, when coupled with the fact that this particular Astra has a manual transmission, there is an overwhelming number of opportunities during which knee-key interactions could occur. To date, a review of all possible cases related to this vehicle has only revealed this one example of the ignition state unintentionally rotating out of the "Run" position. As of the writing of this report, the Saturn Astra has not been included in any of the GM ignition switch-related recalls.

Year	2008
Make	Saturn
Model	Astra
Recalled Vehicle?	No
Gender	Male
Age	Younger
Ignition Switch	Steering Column
Speed at Ignition off	48mph
Belted?	Yes

Figure 102. SHRP 2 Saturn Astra knee-key case.

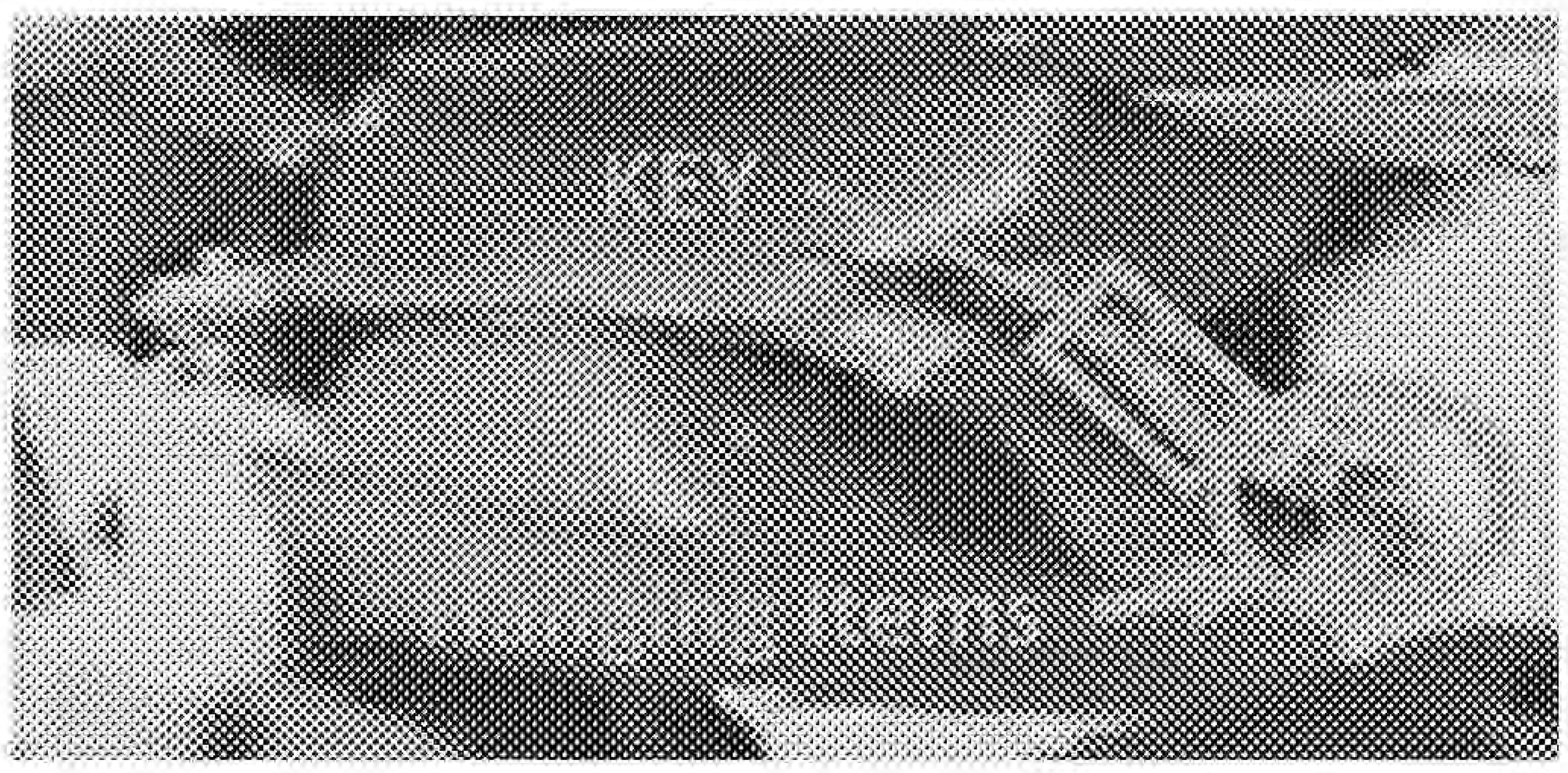


Figure 103. Close-up of keys in Saturn Astra knee-key case.

GM Case #3: 2003 Saturn Ion

In this example, a young male is driving a 2003 Saturn Ion down a divided two-lane road, traveling at approximately 34 mph (Figure 104). The driver reaches down and appears to scratch his right leg, at which point his knee contacts the items hanging from the key chain, altering the vehicle's ignition state. The driver reacts almost immediately, restarting the car and continuing on his way while initially visibly surprised.

Year	2003
Make	Saturn
Model	Ion
Recalled Vehicle?	Yes
Gender	Male
Age	Younger
Ignition Switch	Steering Column
Speed at Ignition off	34mph
Belted?	No

Figure 104. SHRP 2 Saturn Ion knee-key case.

GM Case #4 (hand swipe): 2005 Chevrolet Cobalt

This example involves a young female who is driving a 2005 Chevrolet Cobalt down a two-way road at approximately 43 mph (Figure 105). The driver reaches down towards her right leg, and the brushing movement of her right hand results in a contact with the items hanging from her key chain, at which point the vehicle leaves the "Run" position. The driver's reaction is observed, although the trip file ends as the driver is pulling off of the road with no observed attempt to re-start. Although not an extreme example in terms of attached items, it does appear that this driver has more than a few items attached to her key ring, including what appears to be a rabbit's foot. It is worth noting that subsequent video review of the SHRP 2 NDS flagged data revealed that this driver experienced two other unintentional ignition key rotation events, both classified as inertial-based and discussed earlier within this report.

Year	2005
Make	Chevrolet
Model	Cobalt
Recalled Vehicle?	Yes
Gender	Female
Age	Younger
Ignition Switch	Steering Column
Speed at Ignition off	43mph
Belted?	Yes

Figure 105. SHRP 2 Chevrolet Cobalt knee-key case.

GM Case #5 (Other – hands on top): 2004 GMC Envoy

While traveling at approximately 35 mph upon approach to an intersection, a driver (young male) of a 2004 GMC Envoy places both hands through the steering wheel rim, resting them on top of the steering wheel center (Figure 106). The driver applies pressure to the ignition key with his right hand, then is surprised to see he has turned the vehicle out of the "Run" position. He immediately restarts the vehicle, with his hand still through the steering wheel rim.

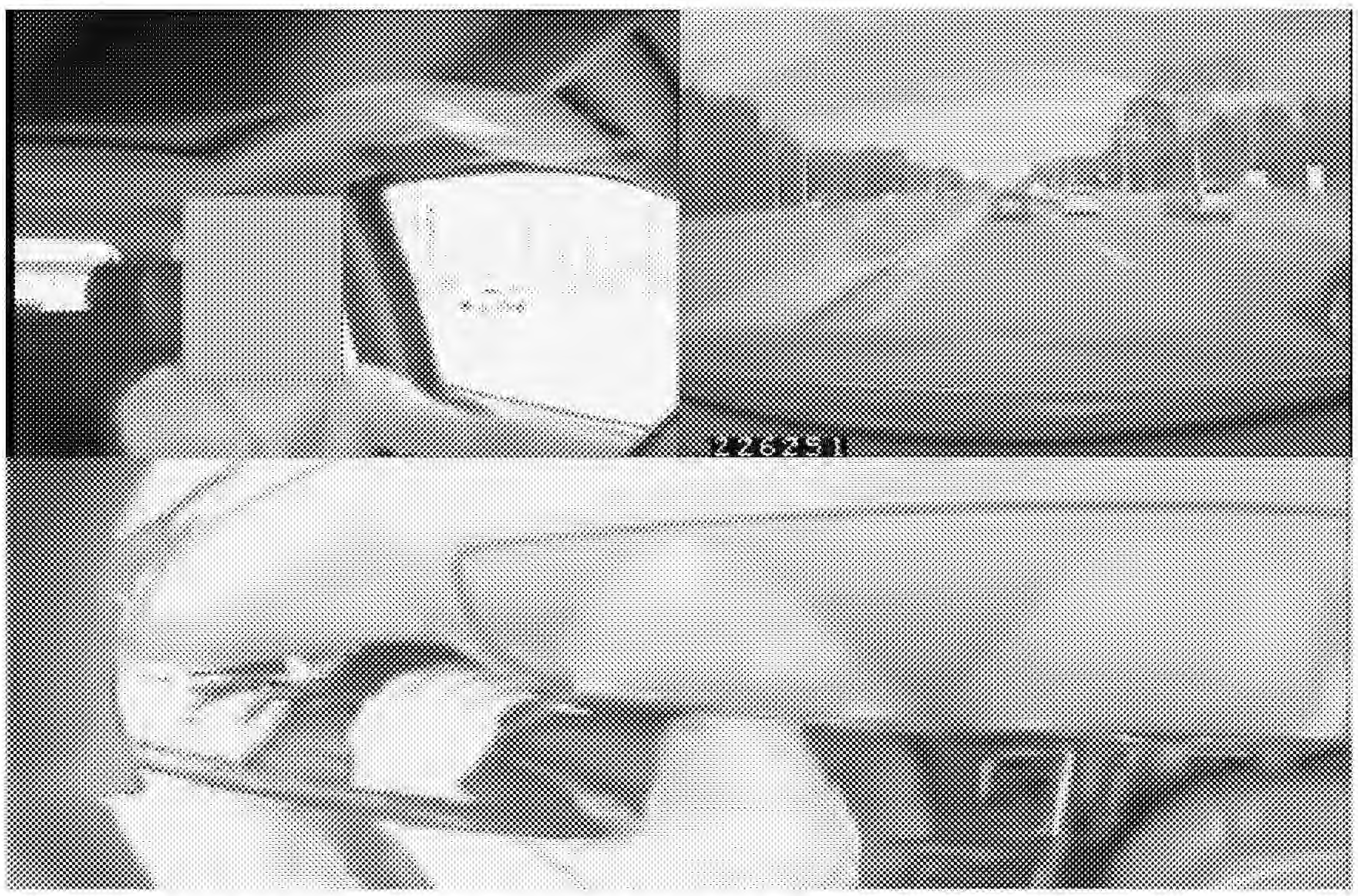


Figure 106. SHRP 2 atypical behavior case (hands on top).

GM Case #6 (Other – passenger interference)

In another non-knee-key-related example, a passenger with a young (likely teenaged) driver reaches over and turns the ignition key (Figure 107). A closer review reveals that, earlier during the trip, the same passenger moved the automatic gear shift into neutral. The passenger performs the same movement prior to turning the ignition key, at which point the driver immediately grabs the ignition key and turns the vehicle back to the "Run" position.

Figure 107. SHRP 2 atypical behavior case (passenger interference).

GM Case #7 (Other – attempt to attach an item to the key chain)

In this example, the driver of a 2009 Chevrolet Malibu is driving down a two-lane road at approximately 51 mph. She is observed applying lip balm, which she then attaches to her key ring (Figure 108). While she is attaching the lip balm to her key chain, she inadvertently turns the ignition key from the "Run" position, something she does not appear to recognize until she turns her full attention back to the driving task. The trip file ends before she is observed making any attempt to re-start the vehicle.

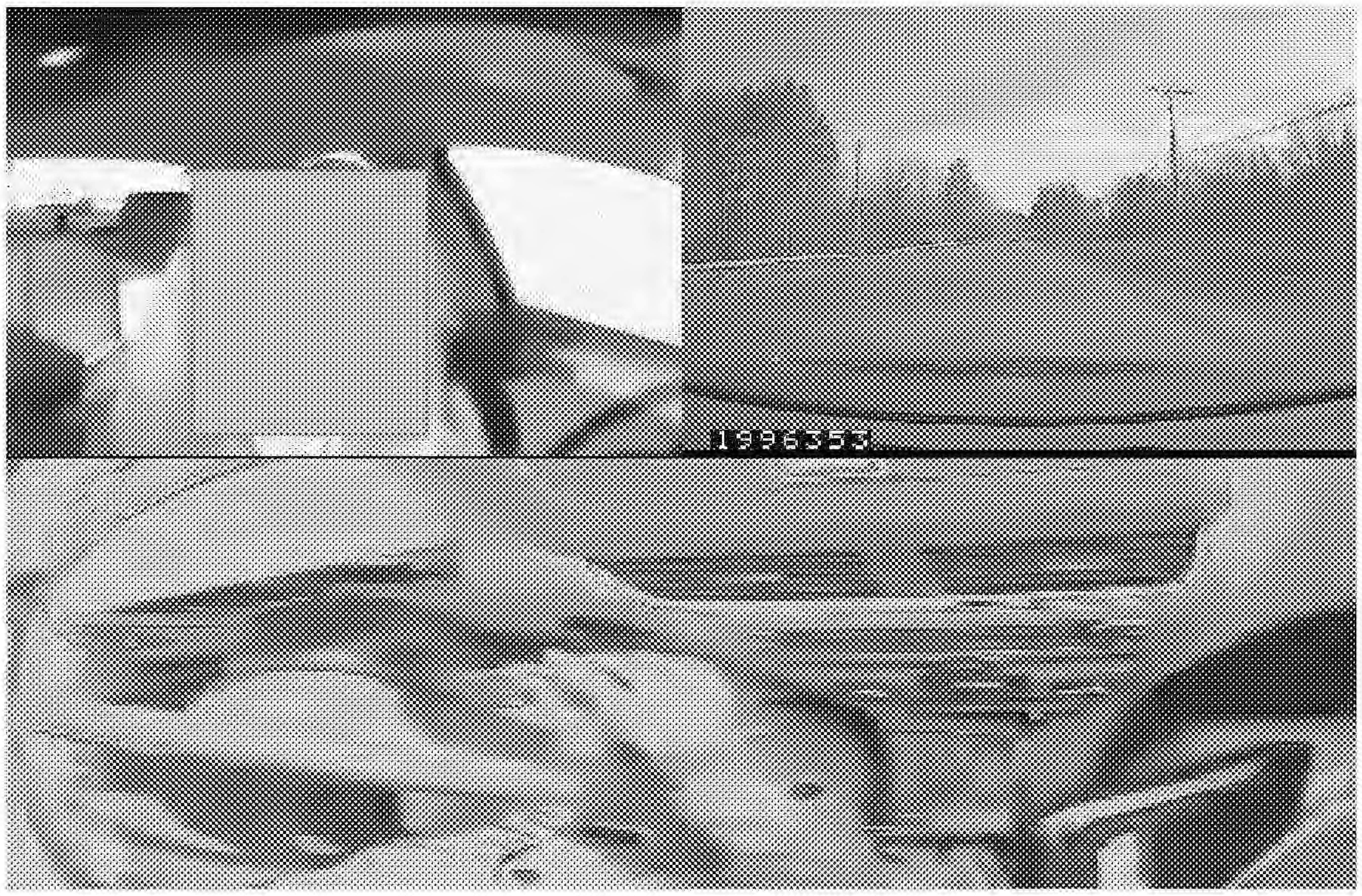


Figure 108. SHRP 2 atypical behavior case (re-attaching item to key chain).

ASSESSING THE GM HANG TAG TEST

Overview

The purpose of the GM hang tag test is to determine whether or not a hang tag or other key/lanyard/novelty item present on a key ring can somehow become lodged in some part of the steering wheel, thus producing a torque that could result in a turn of the ignition switch out of the "Run" position. Figure 109 illustrates a potential hang tag scenario.

Figure 109. Possible hang tag scenario (photo courtesy of GM).

As logged in GM-internal SUFS data provided to the VTTI project team, an issue potentially related to a hang tag occurrence indicates that a dangling key became lodged in the "spokes" of the steering wheel, making it momentarily difficult to steer the vehicle. It is anticipated that this entanglement could occur when the hang tag and any other keys present on the key chain begin a swinging movement due to inherent vehicle kinematics associated with both normal and off-road (i.e., road departure) driving or extreme events. This assumption seems to be particularly true when enough keys attached to the key ring prevent each key from hanging vertically at rest, resulting in a somewhat splayed configuration, or when hang tags or other objects attached to the key ring are longer in length.

Four complaints specific to hang tags (i.e., those that specifically mention the hang tag phenomenon) and two possible complaints (i.e., hang tag not mentioned but could have been an issue based on the nature of the complaint) have been logged in GM-internal data provided to the VTTI project team:

- 2014 Chevrolet Equinox (hang tag complaint logged by consumer in GM-internal SUFS data)
- Chevrolet Equinox (hang tag complaint logged by consumer in SUFS data; model year not specified)
- 2003 Yukon XL Denali (emerging issue of a hang tag complaint)

- K2XX (logged field complaint)
- 2007 GMC Yukon (potential emerging issue)
- 2008 Saturn Astra (potential emerging issue)

It appears that these events tended to occur when large steering wheel movements were made, such as when the driver was making a 90-degree right- or left-hand turn (e.g., turning onto a new road, a parking lot, etc.). Hang tag scenarios also appear to occur within several different GM models for different reasons, as based upon consumer complaints logged to date relative to specific and potential hang tag events.

As with the other ignition switch tests created by GM (i.e., inertial and knee key), the hang tag test was devised to replicate the issue and to determine potential solutions. The hang tag testing revealed that this phenomenon could potentially involve a complex interaction between several variables, including:

- Location of control buttons on the steering wheel,
- Geometry of the back of the steering wheel,
- Ignition switch location and orientation,
- Key head orientation, and
- Key tag length and key ring configuration.

GM engineers have made a number of observations regarding factors that can increase or decrease the probability of a hang tag occurrence. These factors include key ring configuration, steering wheel surface type, the presence of forward switches, the presence of the tuck groove for leather-covered steering wheels, and the clearance between the ignition key head and the steering wheel.

A review of the NHTSA SaferCar website using the key words “hangtag,” “hang tag,” “key,” “steering wheel,” “tag,” and “caught” revealed no GM cases in which a complaint was logged specifically for the hang tag phenomenon. By contrast, there are numerous SaferCar complaint cases that appear to be related to the knee-key issue within GM vehicles (see Table 7).

As described previously, the VTTI project team queried its SHRP 2 NDS data to determine cases during which inadvertent ignition deactivation occurred while the vehicle was moving. The project team found five cases during which an inadvertent change in the ignition switch position occurred due to inertial forces caused by a combination of the mass of the key chain and the road environment and four knee-key cases during which the driver came into contact with the ignition key, the key fob, or the key chain in such a manner as to cause an unintended ignition key rotation out of the “Run” position. However, there were no instances during which a hang tag occurrence was discovered in the SHRP 2 NDS database. As stated, although this database is certainly not all-inclusive, the lack of hang tag phenomenon present in the data would indicate that hang tag issues are rarer occurrences than inertial or knee-key events given the large number of GM vehicles (519 total; Table 3 and Table 4) and the large number of miles driven in those GM vehicles (close to 10 million) available in the SHRP 2 NDS data.

An important factor discovered during the hang tag testing is that increasing the torque required to turn the ignition key will likely not prove to be a solution. As with knee-key issues, the torque required to turn the ignition key out of the "Run" position is notably not a factor within the hang tag phenomenon. This is primarily due to the amount of force that could be generated on the ignition key configuration should the right set of circumstances occur. That is, regardless of whether the torque is 10 or 45 Ncm, enough force could be exerted during certain driving situations to cause a hang tag occurrence that would deactivate the ignition.

Similarly, reducing or eliminating the movement and force placed upon the ignition key by using a hole in the key head design instead of a slot, or using multiple smaller key rings, may not eliminate a hang tag issue. During GM hang tag testing, there were cases during which the hang tag became lodged between part of the steering wheel and the key such that the position applied a force directly to the ignition key head, independent of the ignition key configuration.

It is also important to note that the hang tag phenomenon may also interact with the knee-key scenario since the hang tag can also be contacted and can be moved around by a driver's knee. For example, in a specific SHRP 2 NDS case (2008 Saturn Astra), the driver was large enough that the key chain rested almost horizontally on top of the driver's thigh during normal driving (Figure 103). Even though a hang tag occurrence was not found in the SHRP 2 NDS query, it is conceivable that there would be a greater possibility for a hang tag issue to occur during such an event due to the interaction between the driver's knee and the key chain.

Preliminary Conclusions

The hang tag test is largely subjective. The success or failure of the test is dependent upon the size, shape, and rigidity of the hang tag used. In addition, a prime consideration is how the hang tag or other lanyards, keys, or novelties may move into a position in which they can become lodged in the steering wheel. As is true with the inertial and knee-key phenomena, factors such as the mass and length of the key chain play a pivotal role in hang tag issues.

The VTTI project team's assessment of the hang tag test, as designed, is that it is robust in the sense that it succeeds in finding designs and scenarios that could potentially lead to an inadvertent change in the ignition state. However, whether or not the test is valid for its intended purpose is still questionable due to the rare nature of such an event. The VTTI project team suspects that the current hang tag test is robust enough that it may generate a number of false alarms (i.e., situations during which a vehicle configuration will fail the hang tag test but such a scenario will rarely, if ever, occur during actual driving). It appears that there will be anomalous circumstances during which a hang tag scenario has the potential to move the ignition state out of the "Run" position. That is, if a driver's key chain is long enough or has a large width due to many items on the key chain, there is a possibility that an item can get caught at some location on the steering column.

However, given the relative rarity of the hang tag occurrences as indicated by three independent sources of data (NHTSA, GM, and SHRP 2 NDS), as well as the breadth of factors that could possibly lead to such an occurrence limiting the design options, the VTTI project team recommends that GM consider excluding the hang tag test from its set of ignition switch tests or combining aspects of it with the knee-key test. An additional consideration is that a hang tag scenario may be somewhat lower risk for the driver given the large steering displacement (i.e., large steering wheel movements occurring at lower speeds) found in the hang tag occurrences and potential issues logged with GM to date. The VTTI project team recognizes that serious crashes may still occur if an item from the key chain was to become lodged in the steering wheel during a right- or left-hand turn, but the overall risk is probably much lower compared to inertial and knee-key risks.

The VTTI project team recommends that GM consider eliminating the hang tag test as a separate test. However, this does not mean the team has no recommended countermeasures to ensure that the probability of hang tag occurrence is even further reduced. As with the inertial and knee-key scenarios, and as described in detail in the *Suggested Countermeasures and Design Considerations* section of this report, it is important to limit the number, mass, and length of items that are present on a key chain attached to the ignition key. Therefore, even though the hang tag phenomenon may fall into the "anomalous occurrence" category, drivers should still be made aware of the risks and advised as to the maximum hang tag length and the mass and number of items that can be safely attached to an ignition key. The VTTI project team believes that, if this information is widely disseminated, the hang tag phenomenon will become an even rarer event.

SUGGESTED COUNTERMEASURES AND DESIGN CONSIDERATIONS

The purpose of this section is to outline several thoughts related to controlling the presence of a hazard, either in current or future models of GM vehicles. The hazard in this case is the potential loss of control and safety system deactivation that could occur with an inadvertent rotation of the ignition state out of the "Run" position. The VTTI project team understands that many of the ideas presented herein are not new; in fact, most of these ideas have been considered, or are currently under consideration, by GM engineers. However, in the interest of comprehensive system safety, the VTTI project team believes it is important to systematically outline the options and suggestions regardless of their source.

When considering countermeasures for hazard elimination or mitigation, the following strategy, or a variable thereof, has proven to be very effective:

1. Consider eliminating, or at least mitigating, the hazard through design changes.
2. If the hazard cannot be eliminated, provide a guard (often a physical one) between the hazard and the user.
3. If the hazard cannot be largely eliminated through design or use of a guard, establish laws or administrative rules to protect those involved.
4. If there are still hazards present, train individuals about the nature of the hazard, its consequences, and strategies for remaining safe.
5. If, after the steps above have been considered and there is still a hazard present, enlist "persuasion" injury control techniques.

Design for Hazard Elimination or Mitigation

GM has embarked on three strategies to help mitigate the hazard defined above (i.e., inertial, knee-key, and hang tag tests).

However, there are some design strategies that may further mitigate, and ultimately eliminate, the hazard. One design strategy that should be considered for newer vehicle models is making the necessary changes to the controller area network (CAN) bus message to keep the airbags active until the vehicle speed reaches 5 mph. Thus, if the vehicle stalls for any reason, including common occurrences such as running out of gas, the passive safety systems are active until the vehicle is nearly stopped. The VTTI project team realizes that, as with all design strategies, there are unintended consequences that should be considered. In this instance, keeping the systems active at 5 mph or less may inadvertently create problems during such scenarios as a parking lot collision activation with passengers unbelted and out of position.

A future design solution could also include changing the ignition switch placement and/or orientation or expanding the use of a pushbutton start/stop, as is becoming more common in newer vehicle models. Pushbuttons are not without their own set of issues, such as drivers forgetting to turn off the vehicles. In addition, the VTTI project team learned through first-hand experience at the GM MPG that pushbuttons can also be

inadvertently pressed. An example is shown in Figure 110 in which a non-GM vehicle uses a toggle switch to control the ignition state. The toggle switch is located in close proximity to other toggle switches, thereby greatly increasing the potential for inadvertent ignition deactivation while driving. This example illustrates the importance of making the design of an ignition switch a safety priority across the automotive industry. Specifically, safety design issues must be carefully considered, including the type of ignition control, location, presence of a shroud, and length of pushbutton/switch press necessary to change the vehicle state.

Figure 110. Location of ignition switch toggle in non-GM vehicle.

Designing for hazard elimination or mitigation also currently includes the GM recall effort aimed at increasing the inertial force required to rotate the ignition state out of the “Run” position. As described, increasing the force will eliminate many of the inertial issues that may result in an unintended change in the ignition switch position. However, as was described in the knee-key and hang tag sections, increasing the inertial force requirement would not eliminate, or probably would not even mitigate, cases during which there is physical contact with the ignition key itself or in cases when a hang tag or other key ring object becomes somehow caught or entangled in the steering wheel. Therefore, meeting the design specifications discussed within this report will further help mitigate the hazard substantially, and may even eliminate it.

Another design solution that will mitigate inertial issues is the use of a hole in the center of the ignition key head instead of a slot. The center hole design eliminates a moment arm that, in combination with the key chain mass or a force exerted from contact with the key chain, can move the ignition key out of the “Run” position. The VTTI project team believes this mitigation strategy will be successful. However, care must be taken to supply a key ring that is of a size that cannot bind in the hole itself or on the edge of

the ignition key, thus creating a moment arm regardless of the ignition key head design, as was discussed in *Assessing the GM Inertial Test*. It should be noted that the location of the hole in the ignition key head must be central to effectively minimize the potential of a moment arm to act on the ignition key and cause an inadvertent ignition deactivation. For example, a hole located on the edge of the ignition key may result in a concentrated force acting upon the ignition key, thus increasing the potential to rotate the key out of the "Run" position. An example of this type of ignition key head design is illustrated in Figure 111, which shows a Jeep Cherokee ignition key. Another design solution would be to distribute ignition keys with no hole or slot, although this would likely inconvenience many drivers, thus raising issues of persuasion and compliance cost, as described below.

Figure 111. Jeep Cherokee ignition key with edge hole design.

For vehicles with a large, integrated key fob where physical contact with the ignition key is an issue, an obvious solution would be a smaller, perhaps separate key/fob combination. As discussed previously, this mitigation strategy was implemented for the recalled fifth-generation Chevrolet Camaros. It is important to note that this strategy is also very dependent upon the location and orientation of the ignition key. Thus, some vehicles with large key fobs may not experience this issue at all. Due to persuasion aspects described below, such ignition key head design configurations would be particularly effective if the configuration could be changed without sacrificing fob functionality.

Guarding Against the Hazard

In this case, guarding against the hazard would include somehow shielding the ignition key, key fob, or pushbutton or moving the ignition switch location altogether. Of course,

other ignition switch locations could potentially be worse or at least not as ideal, particularly when considering out-of-position or unbelted drivers traveling in both on- and off-road conditions.

Laws or Administrative Rule

In this case, laws cannot be established by an independent OEM. However, an OEM can apply an administrative rule in a case such as this by communicating a circumstance during which the vehicle warranty is voided should a rule be violated. Considering the three types of events (i.e., inertial, knee-key, and hang tag) that could result in an unintended ignition key rotation, a long or overly heavy key chain could lead to a potential knee-key or hang tag scenario. Thus, a warning to the vehicle owners, with a statement that the warranty may be voided should the warning not be heeded, may prove effective in helping eliminate or mitigate unintended ignition deactivation. As will be described in the persuasion section below, such an approach would likely increase warning compliance more so than a simple warning by itself.

Training

Simple training is underway by GM in the form of instructions to consumers to remove all objects from their key rings, trade in their keys or get an insert, etc. However, this training will not be completely effective due to the difficulty in reaching all GM vehicle owners and issues of persuasion. In this case, as will be described below, training effectiveness will likely be limited due to the cost of compliance with the training content. Thus, while this is a very important and positive step, it cannot be solely relied upon to help mitigate the hazard.

It is important to note that GM recognizes this step as temporary until other design solutions (e.g., new ignition key with a hole instead of a slot) can be instituted.

Persuasion

Persuasion injury control is always the last resort in mitigating, or eliminating, the hazard simply because it is generally the least effective control technique. Although often an important part of an overall control strategy, persuasion techniques used alone often see compliance rates no greater than 20 or 25 percent. In this case, GM is trying to convince drivers to separate their keys so that they have only one key in the ignition. This is an important step, but compliance may be limited due to compliance cost. That is, it is inconvenient to carry multiple sets of keys, and a single key may become lost or misplaced more easily. In the case of a large key/fob combination, GM is potentially asking the driver to cede a convenience feature by using a smaller key with limited or non-existent remote functionality. As discussed above, if a fob can be configured that mitigates the hazard while maintaining functionality, it would be an ideal scenario in terms of compliance.

GM has reached out to its consumers through two different means: 1) The GM dealer network via recall notices and 2) A national information campaign. For example, GM placed a full-page ad in *USAToday* to try to reach consumers. A cursory review of the ad campaign leads the VTTI project team to believe that it is well done, in the sense that it is persuasive and easy to understand. However, the team always recommends a prospective and retrospective evaluation of the effectiveness of any such program.

For future GM vehicle models, it may be worthwhile to consider the use of an interactive warning label to add redundancy to any control strategy. In this case, a warning label would be affixed to the new vehicle key chain that indicates the maximum length of a key chain and the maximum number of items that should be hung from the ignition key, thus controlling mass and length to some extent. Since the warning label will be removed in almost all cases, a simple associated warning (e.g., “Nothing on your key chain should be longer than the attached GM key fob”) would help drivers remember the maximum length and establish a simple rule to follow. This strategy would likely further help reduce the risk of future unintended changes in the ignition switch position.

CONCLUSIONS AND SUGGESTED FOLLOW-ON PROJECTS

During its evaluation of the GM ignition switch tests, VTTI determined the following:

1. Inertial tests conducted at the GM MPG are robust and valid in determining scenarios during which inertial effects could rotate the ignition switch out of the "Run" position.
    - These tests will uncover the majority of inertial-based issues.
    - The tests appear to have a relatively low miss/false alarm rate (i.e., GM is finding what needs to be found during its inertial testing).

2. MPG testing could be reduced or even potentially eliminated if a large enough database of static models is created to robustly determine inertial effects.

3. The GM knee-key test, although somewhat subjective, is acceptable for examining this risk within existing vehicles.
    - However, enhancements are recommended to standardize the knee-key test process and quantify/improve results for future testing.
    - The potential exists to incorporate knee-key criteria into the current ergonomic design model at GM, further reducing future vehicle design issues relative to ignition switches.

4. The GM hang tag test is robust to the point of creating false alarms.
    - Hang tag is a rare event that is highly variable.
    - Hang tag events often occur at lower speeds, making a hang tag event generally less risky compared to inertial or knee-key events.
    - However, lessons learned from hang tag testing to date can and should be considered in future designs of GM vehicles.

5. The GM hang tag test should be eliminated as a separate test and combined with knee-key testing/modeling.
    - VTTI believes that a significant portion of hang tag issues involve knee contact.
    - Pure kinematic hang tag cases are probably very rare and may involve many keys/items hanging from the ignition key.

6. A primary issue in all three ignition switch scenarios is what drivers choose to hang from the ignition key (e.g., lanyards, other keys, fobs, etc.).
    - Although the majority of unintended changes in the ignition switch position can be eliminated through testing and design, educating and persuading drivers to adhere to reasonable guidelines remains an important control strategy.
    - A variety of countermeasures are suggested for consideration.
    - This is an industry-wide issue.

In summary, VTTI found through its independent analyses that, overall, GM engineers have made significant progress in creating a robust series of tests that have already

performed well and will continue to perform as constructed. That is, GM is using a series of tests that will determine the likelihood of ignition switch issues, thus allowing for countermeasures to be developed for current vehicles, with the ultimate goal of implementing and enhancing these tests in future vehicle models to design out any ignition switch issues before they occur.

As a result, VTTI believes the majority of existing ignition switch cases have been identified by GM, and the company's control strategies should result in a substantial reduction of events during which the ignition state unintentionally rotates out of the "Run" position.

However, the VTTI project team feels that four potential follow-on projects may be performed to help further mitigate, and ultimately eliminate, ignition switch issues experienced within GM vehicles. Undertaking such projects is solely at the discretion of GM.

1. Review all identified occurrences in the SHRP 2 NDS database during which the ignition state in GM vehicles changes out of the "Run" position to characterize contributing factors, to the greatest extent practical.
2. Expand the review of off-road crash and near-crash events identified in the SHRP 2 NDS database to further refine the off-road dynamic environment and driver body position (belted and unbelted), as available.
3. Analyze events during which high-speed, off-road accelerations were discovered and compare these events to GM data to further validate the inertial test.
4. Perform cross-coupling of in-vehicle data between inertial inputs.

Potential Follow-on Recommendation #1: Review All GM Ignition Deactivation Events

As discussed previously, a full-scale analysis of the SHRP 2 NDS database exceeded the scope of this effort, so it was not possible to review all flagged events based on the query outputs. Therefore, it is recommended that GM undertake a follow-on project during which the VTTI project team will perform a thorough analysis of all GM vehicle cases available in the SHRP 2 NDS database during which a change in the ignition state was flagged to more thoroughly capture any potential inertial, knee-key, and/or hang tag events.

Potential Follow-on Recommendation #2: Expand Review of Off-road Events

As of this writing, there were 312 off-road crashes or near-crashes identified in the SHRP 2 NDS database. These crash/near-crash events typically involve driving over curbs, into the median, brief off-road excursions, etc. As such, they provide a useful comparison to accelerations experienced by vehicles during the inertial tests conducted at the GM MPG. A thorough review of off-road video within the SHRP 2 NDS database would further help assess the potential for inertial, knee-key, and/or hang tag events to occur. However, such review was not feasible within the time constraints associated with this project. Therefore, the VTTI project team recommends that a follow-on task be

conducted during which data reductionists will provide a thorough analysis of all 312 potential off-road crash or near-crash events to determine if any involve an unintentional change in the ignition switch position. It is also possible during a review of the SHRP 2 NDS off-road events to examine driver movement during higher impact cases and the movement of belted versus unbelted drivers during such events. This information could help provide a starting point for defining the dynamics and biomechanics experienced during crash or near-crash events. As discussed, such benchmarks do not currently exist for testing purposes.

Potential Follow-on Recommendation #3: Analyze High-speed, Off-road Acceleration Events

The SHRP 2 NDS database of crashes and near-crashes currently includes 312 off-road crash and near-crash events. The off-road events recorded in the SHRP 2 NDS database included driving off the road, over curbs, and driving into the median. Of these 312 off-road events, 18 triggered a high-speed recording feature of the DAS, thus indicating a potential crash event. Because of the time constraints associated with this project, the data associated with these high-speed, off-road events have not been thoroughly analyzed. However, an initial, incomplete comparison of the GM MPG events to the high-speed, off-road SHRP 2 data showed that there is a possibility that the GM MPG events may not completely capture and exceed the types of inertial effects experienced during high-speed, off-road driving events. It should be noted that this initial comparison found that the GM MPG events produce greater accelerations at the extremes of the 99.9 percent data, so such events should impart inertial loads that are similar or exceed those found in the SHRP 2 off-road data. However, a follow-on study should be undertaken to more thoroughly analyze and compare the GM MPG data to the SHRP 2 high-speed, off-road data to determine any instances during which the GM MPG events may not capture and exceed the SHRP 2 NDS high-speed, off-road data.

Potential Follow-on Recommendation #4: Perform Cross-coupling of Acceleration Content

During this project, inertial inputs across three separate acceleration parameters (i.e., longitudinal, lateral, and vertical) were compared using GM MPG data and SHRP 2 NDS data. However, the combined acceleration content was not thoroughly analyzed due to time constraints. Therefore, it is recommended that such cross-coupling of the acceleration parameters be analyzed and compared across the GM MPG and SHRP 2 NDS data to determine if the GM MPG events capture and exceed all three acceleration parameters.

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APPENDIX A. VTTI FACILITIES

Headquartered at VTTI, the Smart Road is a 2.2-mile, controlled-access facility managed by the Institute and owned and maintained by the Virginia Department of Transportation. The road itself is built to Federal Highway Administration specifications and features seven roadside equipment units and two mobile roadside equipment sites that facilitate connected-vehicle communications; an optical fiber communication system; Ethernet fiber transceivers and Ethernet switches; a connected-vehicle-compatible intersection controller model; varying pavement sections and in-pavement sensors; 75 weather-making towers capable of producing snow, rain, and fog; a differential GPS base station for precise vehicle locating; a signalized intersection with complete signal phase and timing control; a wireless mesh network variable control system; and variable pole spacing designed to replicate 95 percent of national highway lighting systems.

The Northern Virginia Connected-vehicle Test Bed was opened during 2013 and supports real-world connected-vehicle/infrastructure research on a larger scale along the most congested roadway in the United States. The test bed is a Virginia Department of Transportation facility developed in partnership with VTTI, the University of Virginia, and Morgan State University as part of the Connected Vehicle/Infrastructure University Transportation Center funded by the U.S. Department of Transportation. The facility features: 43 wireless roadside equipment units that enable connected-vehicle communications along Interstate 66, Interstate 495, U.S. 29, and U.S. 50 (with plans to add 25 wireless roadside units during 2014); two mobile roadside equipment sites; and variable traffic conditions and roadway types, including four major merge/diverge locations, two metro stations, high-occupancy toll lanes, and major roadway construction.

The Virginia International Raceway in Alton, Va., was established as a cooperative agreement through which VTTI can conduct projects in a multi-use testing environment that includes both closed-course and open traffic conditions. On site at the raceway is a resort that features a 12-unit complex of residential villas, a lodge, a club house, a full-service restaurant and tavern, administrative offices, and a spa. The raceway track can be configured to five different courses ranging from 1.1 miles to 4.2 miles and includes such topography as hairpin curves and blind passes.

The Virginia International Raceway is also home to the Virginia Motorsports Technology Park, which contains the Southern Virginia Vehicle Motion Labs (SoVa Motion) and the National Tire Research Center, an affiliated company of VTTI. The National Tire Research Center/SoVa Motion feature the only machine in the world that generate force-and-moment tire data at 200 mph under realistic combined loading conditions, which is twice the capacity of other tire-test machines. Personnel at this facility have expertise in creating hardware and math models and have the capacity to virtually and physically develop products that increase the performance of vehicles and tires. Current projects conducted at the National Tire Research Center/SoVa Motion range from customer-prescribed tire and vehicle tests to developing vehicle and tire testing and

analysis tools for OEMs. This facility was established as a true third-party entity, which means it is not affiliated with any vehicle OEM, component OEM, or race organization, thereby providing unbiased test procedures and data/analyses.

VTTI also has access to a 10,000 square foot Crash Sled Lab housed at the Virginia Tech Corporate Research Center. The lab contains a 1.4 meganewton ServoSled System crash sled and is the only facility in the world with unique capabilities that include high-rate impact testing and high-rate imaging. These resources facilitate a better understanding of injury mechanisms and provide researchers with the capability to develop better mitigation schemes and protection systems.

APPENDIX B. VTTI "KEY CHAIN RODEO"

	Total Weight	Length (measured from center of smallest ignition switch)	Participant #	Hole/Slider
1	4.5 oz.	3.5"	F1	S
2	4.5 oz.	4.75"	M1	S
3	4 oz.	3.5"	M2	S
4	3.5 oz.	5"	F2	S
5	1 oz.	3.5"	M3	S
6	4 oz.	3.75"	M4	S
7	3 oz.	6"	F3	S
8	5.5 oz.	4.5"	F4	S
9	4 oz.	6"	M5	S
10	1.5 oz.	4"	M6	S

	Total Weight	**Length (measured from center of smallest ignition switch)**	**Participant #**	**Hole/Slider**
11	4.5 oz.	6.5”	F5	S
12	2 oz.	3.25”	F6	S
13	3 oz.	5.5”	M7	H
14	2.5 oz.	10.5”	F7	S
15	8 oz.	6.5” (w/out lanyard)	F8	H
16	3.5 oz.	4”	F9	H
17	7 oz.	20.5” (with lanyard) 4.5” (w/out lanyard)	F10	H
18	4.5 oz.	5”	F11	S
19	4 oz.	6.5”	F12	S
20	4 oz.	20” (with lanyard) 6.5” (w/out lanyard)	F13	S

	Total Weight	Length (measured from center of smallest ignition switch)	Participant #	Hole/Slider
21	8 oz.	6.75”	F14	S
22	5 oz.	6.5”	F15	S
23	2.5 oz.	7”	F16	S
24	2 oz.	4.75”	M8	S
25	5 oz.	5”	M9	S
26	3.5 oz.	6.25”	M10	S
27	2 oz. (no car keys visible)	4.25”	M11	H
28	2 oz.	4.25”	M12	S
29	4 oz.	3.5”	M13	S
30	5 oz.	6.5”	M14	H

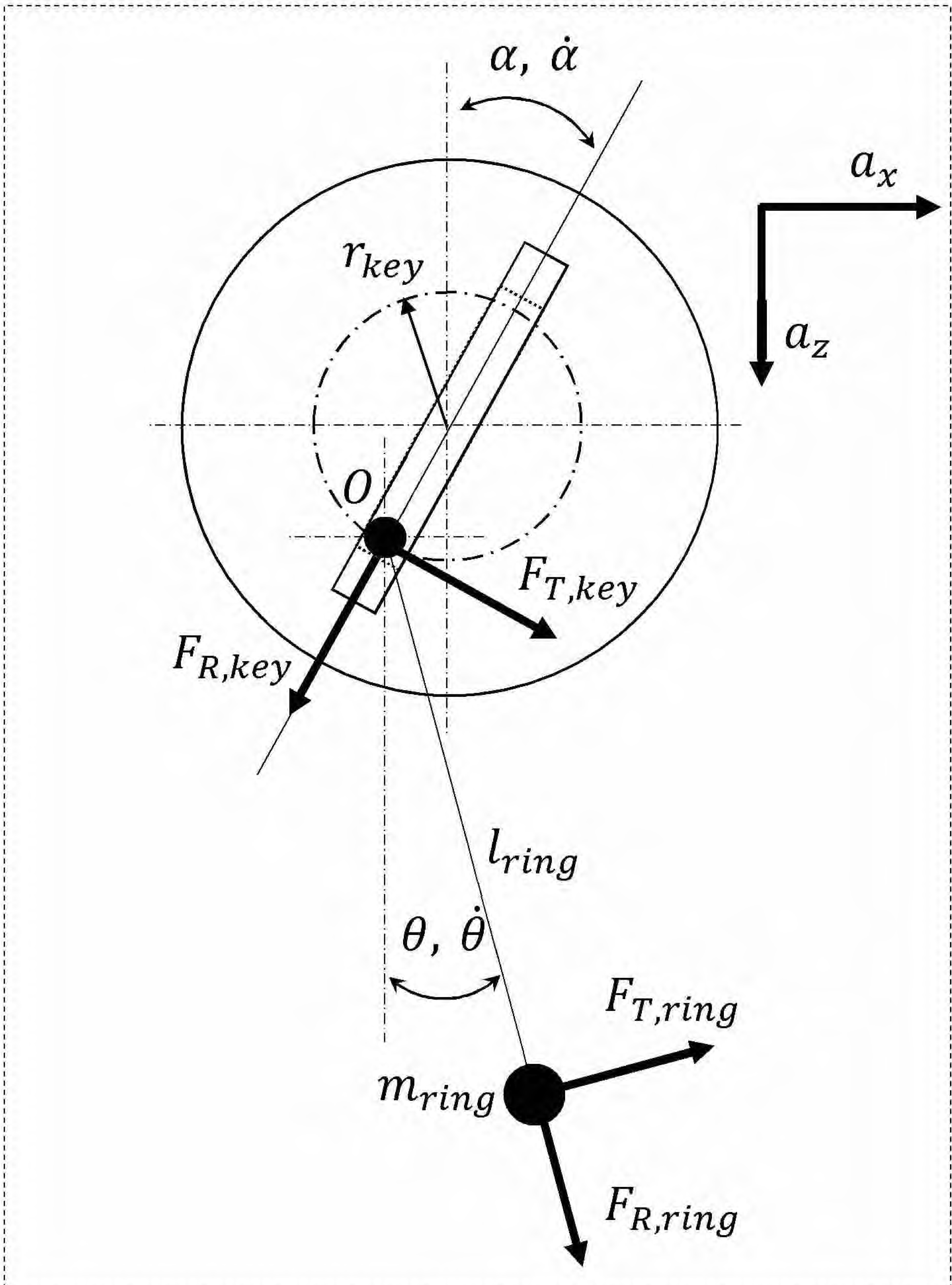
	Total Weight	Length (measured from center of smallest ignition switch)	Participant #	Hole/Slider
31	7.5 oz.	6.25”	M15	H
32	3 oz.	4.5”	M16	S
33	6 oz.	5.5”	M17	S
34	3 oz.	5.75”	M18	S
35	1.5 oz.	2.75”	M19	S
36	3 oz.	4”	M20	S
37	3 oz.	3.75”	M21	S
38	1.5 oz.	3.75”	F17	S
39	6.5 oz.	8.5”	M22	H
40	4.5 oz.	6”	F18	H

	Total Weight	Length (measured from center of smallest ignition switch)	Participant #	Hole/Slider
41	2 oz.	3.25"	M23	S
42	0.5 oz.	2.5"	M24	S
43	3 oz.	6.25"	M25	S
44	3 oz.	4.25"	F19	S
45	1 oz.	3.5"	F20	H
46	4 oz.	3.5"	M26	S
47	1 oz.	5"	F21	S
48	1.5 oz.	3.25"	F22	S
49	2 oz.	3.75"	F23	S
50	5 oz.	6.75"	M27	S

	Total Weight	Length (measured from center of smallest ignition switch)	Participant #	Hole/Slider
51	3 oz.	4.25"	F24	S
52	5 oz.	4"	F25	S
53	4 oz.	5.25"	F26	S
54	3 oz.	3"	M28	S
55	1.5 oz.	3.5"	M29	S
56	2 oz.	5"	M30	H
57	5 oz.	5"	M31	S
58	6 oz.	4.5"	M32	H
59	4.5 oz.	4.25"	F27	S
60	5.5 oz.	6"	M33	H

APPENDIX C. INERTIAL PREDICTIVE MODEL

Herein, the VTTI project team derives the equations of motion that govern the dynamic behavior of the key model system described in *Assessing the GM Inertial Test*.



The pendulum model above uses the following variable definitions:

- $\theta, \dot{\theta}$ is the angular position/velocity of the key ring mass relative to vertical
- $\alpha, \dot{\alpha}$ is the angular position/velocity of the key in the ignition relative to vertical

- r_{key} is the distance from the center of the key to the center of the key ring attached to the key
- l_{ring} is the distance from the center of the key ring to mass representation of the point mass, representing the keys and tokens hanging from the key ring
- m_{ring} is the mass of the point mass used to represent the keys and tokens hanging from the key ring
- a_z and a_x are the inertial accelerations acting on the key ignition system

Two different sets of orthogonal force vectors are also shown in the diagram that represent the tangential and radial forces acting on the key ignition system and the pendulum mass:

- $F_{T,key}$ is the tangential force acting on the key to move the switch out of the "Run" position
- $F_{R,key}$ is the radial force acting on the key
- $F_{T,ring}$ is the tangential force acting on the key ring pendulum mass, which causes the pendulum to rotate about point O
- $F_{R,ring}$ is the radial force acting on the key ring pendulum

The diagram provided above and the definitions can be used to calculate the reaction force at point O and, hence, the tangential force acting on the key that may cause key rotation.

First, it is necessary to define the equations of motion for the key. To develop the equations of motion, a new variable is going to be introduced. Let

$$\gamma = \theta + \alpha$$

Be the angle between the arm of the pendulum and the key head. If I_{ign} is the mass moment of inertia of the key ignition assembly about the rotational axis of the key, then

$$I_{ign} \cdot \ddot{\alpha} = r_{key} \cdot F_{T,key} = T_{key}$$

Where T_{key} is the torque of the key required to turn the ignition. Using the diagram, geometry, and the fact that the key ring is not constrained in the longitudinal direction, $F_{T,key}$ can be defined as

$$F_{T,key} = F_{R,ring} \cdot \sin\gamma$$

Under the vertical and longitudinal accelerations combined with the gyroscopic loads associated with the swinging of the pendulum, $F_{T,ring}$ and $F_{R,ring}$ will satisfy the following equations:

$$F_{T,ring} = m_{ring} \cdot a_x \cdot \cos\theta - \left(m_{ring} \cdot a_z + m_{ring} \cdot g\right) \cdot \sin\theta$$

$$F_{R,ring} = \left(m_{ring} \cdot a_z + m_{ring} \cdot g\right) \cdot \cos\theta + m_{ring} \cdot a_x \cdot \sin\theta + m_{ring} \cdot \dot{\theta}^2 \cdot l_{ring}$$

Note the addition of the centripetal acceleration term in the calculation of $F_{R,Key}$.

The equations of motion for the pendulum aspect of the system can be written as:

$$I_{ring} \cdot \ddot{\theta} = l_{ring} \cdot F_{T,ring}$$

Because the mass for the pendulum is assumed to be a point mass, I_{ring} is defined as:

$$I_{ring} = m_{ring} \cdot l_{ring}^2$$

Substituting for $F_{T,ring}$, then:

$$\ddot{\theta} = \frac{m_{ring} \cdot a_x \cdot \cos\theta - \left(m_{ring} \cdot a_z + m_{ring} \cdot g\right) \cdot \sin\theta}{m_{ring} \cdot l_{ring}}$$

Or:

$$\ddot{\theta} = \frac{a_x \cdot \cos\theta - (a_z + g) \cdot \sin\theta}{l_{ring}}$$

The equations can be written in terms of two single order differential equations by letting $x_1(t) = \theta(t)$ and $x_2(t) = \dot{\theta}(t)$ and substituting as

$$\dot{x}_1(t) = x_2(t)$$
$$\dot{x}_2(t) = \frac{a_x \cdot \cos x_1(t) - (a_z + g) \cdot \sin x_1(t)}{l_{ring}}$$

where a_x and a_z are the acceleration inputs to the system.

Properties of Ignition Torque

The inertial force acting on the key can be written as:

$$F_{T,key} = F_{R,ring} \cdot \sin\gamma$$

$$F_{R,ring} = \left(m_{ring} \cdot a_z + m_{ring} \cdot g\right) \cdot \cos\theta + m_{ring} \cdot a_x \cdot \sin\theta + m_{ring} \cdot \dot{\theta}^2 \cdot l_{ring}$$

Substituting results in:

$$F_{T,key} = \left(\left(m_{ring} \cdot a_z + m_{ring} \cdot g\right) \cdot \cos\theta + m_{ring} \cdot a_x \cdot \sin\theta + m_{ring} \cdot \dot{\theta}^2 \cdot l_{ring}\right) \cdot \sin\gamma$$

Or:

$$F_{T,key} = m_{ring} \cdot \left[(a_z + g) \cdot \cos\theta \cdot \sin\gamma + a_x \cdot \sin\theta \cdot \sin\gamma + \dot{\theta}^2 \cdot l_{ring} \cdot \sin\gamma\right]$$

And the inertial torque acting on the key trying to cause key rotation is:

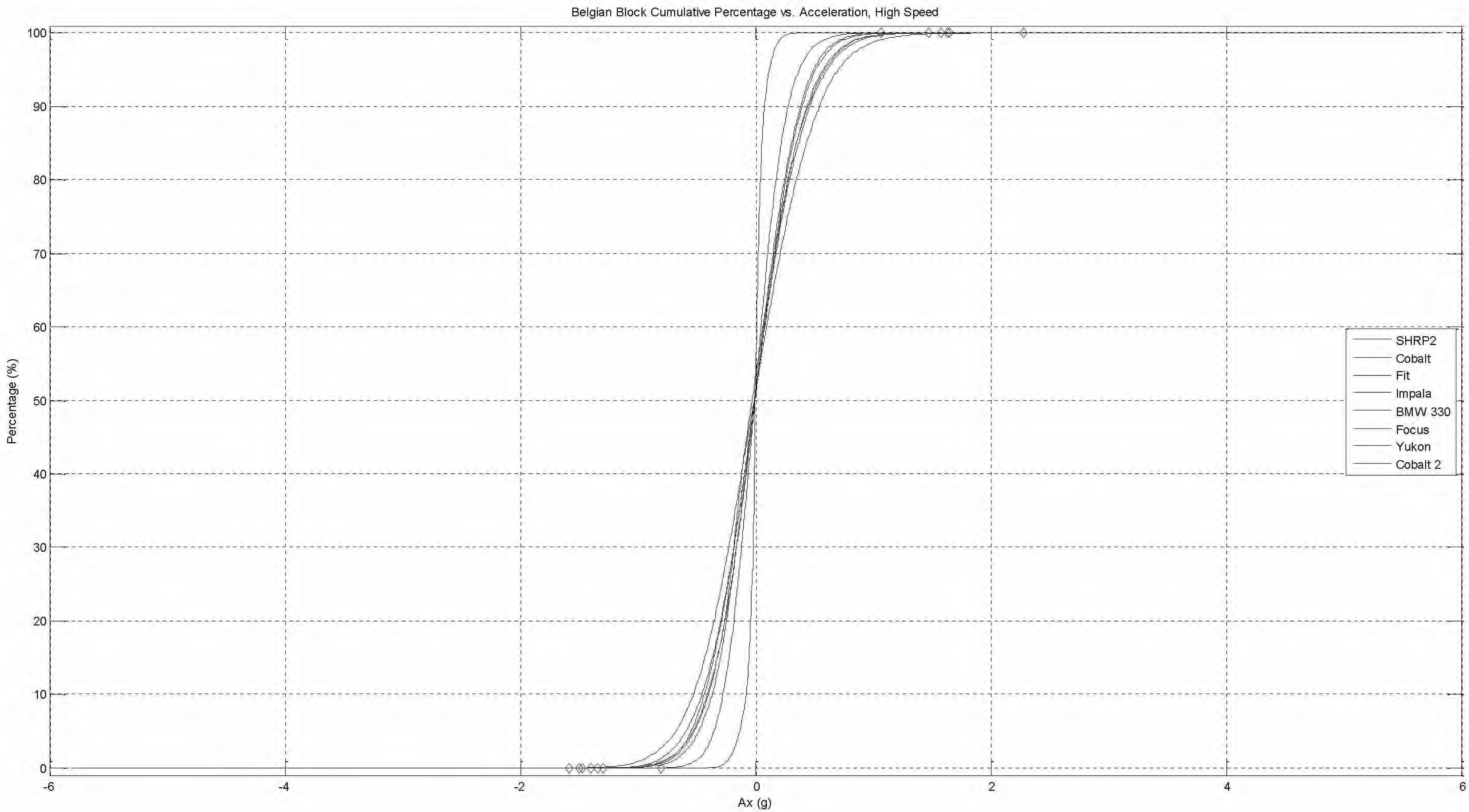
$$Torque_{key} = r_{key} \cdot F_{T,key}$$

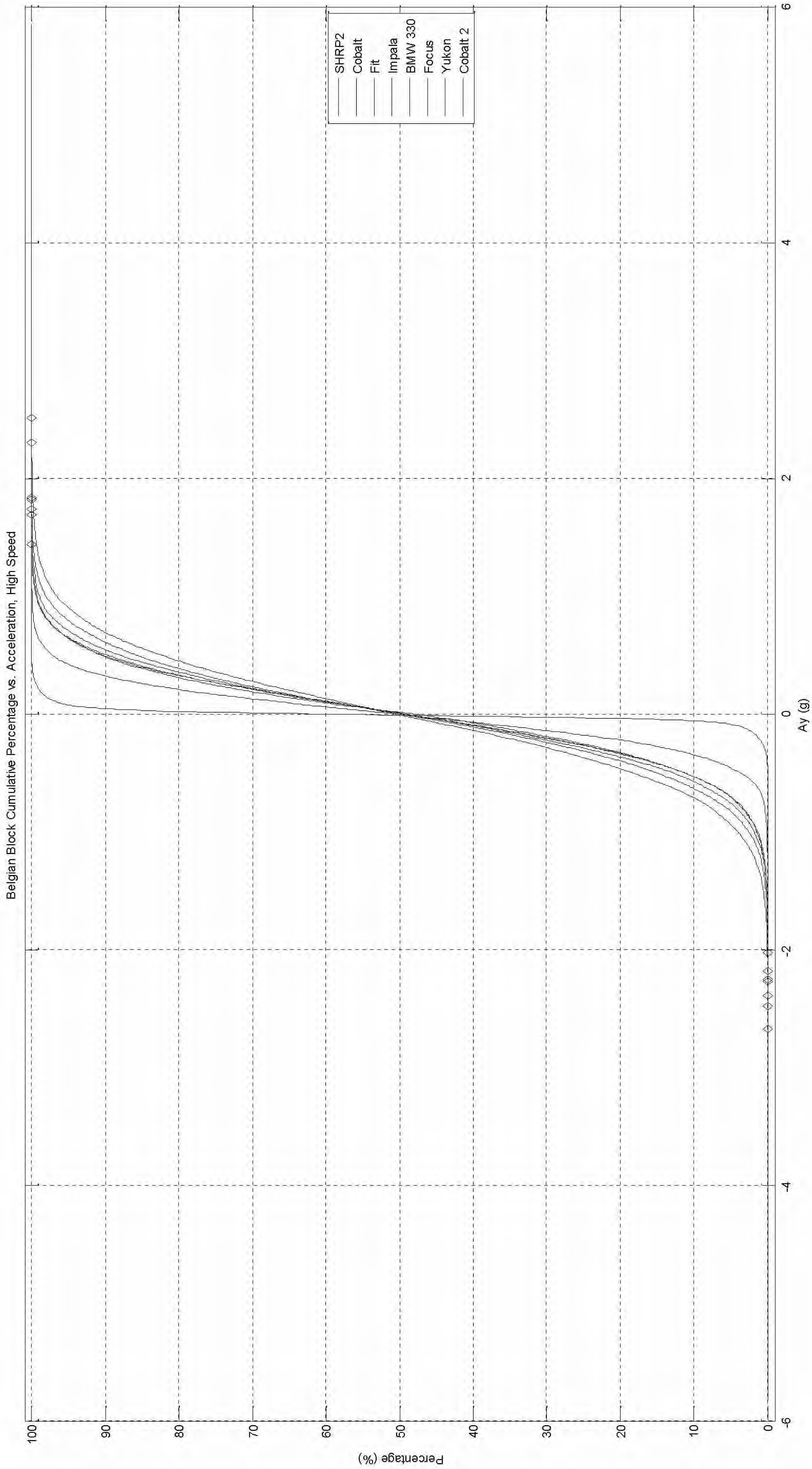
Substitution of $F_{T,key}$ results in the final equation:

$$Torque_{key} = r_{key} \cdot m_{ring} \cdot \left[(a_z + g) \cdot \cos\theta \cdot \sin\gamma + a_x \cdot \sin\theta \cdot \sin\gamma + \dot{\theta}^2 \cdot l_{ring} \cdot \sin\gamma\right]$$

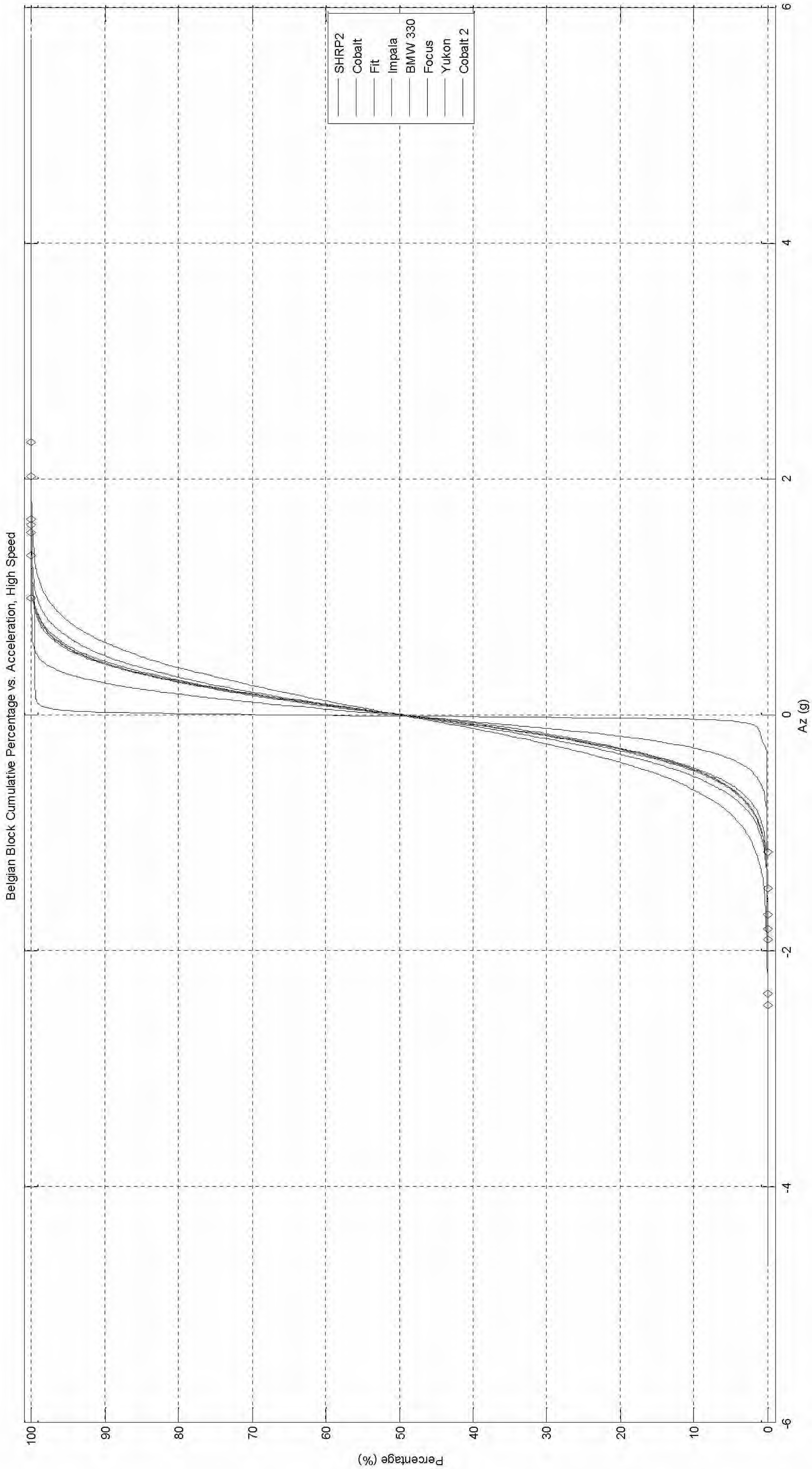
APPENDIX D. SHRP 2 NDS VS. GM MPG DATA COMPARISON PLOTS

Belgian Block, High-speed 100% Plots




Belgian Block Cumulative Percentage vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Ay (g)
100
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6

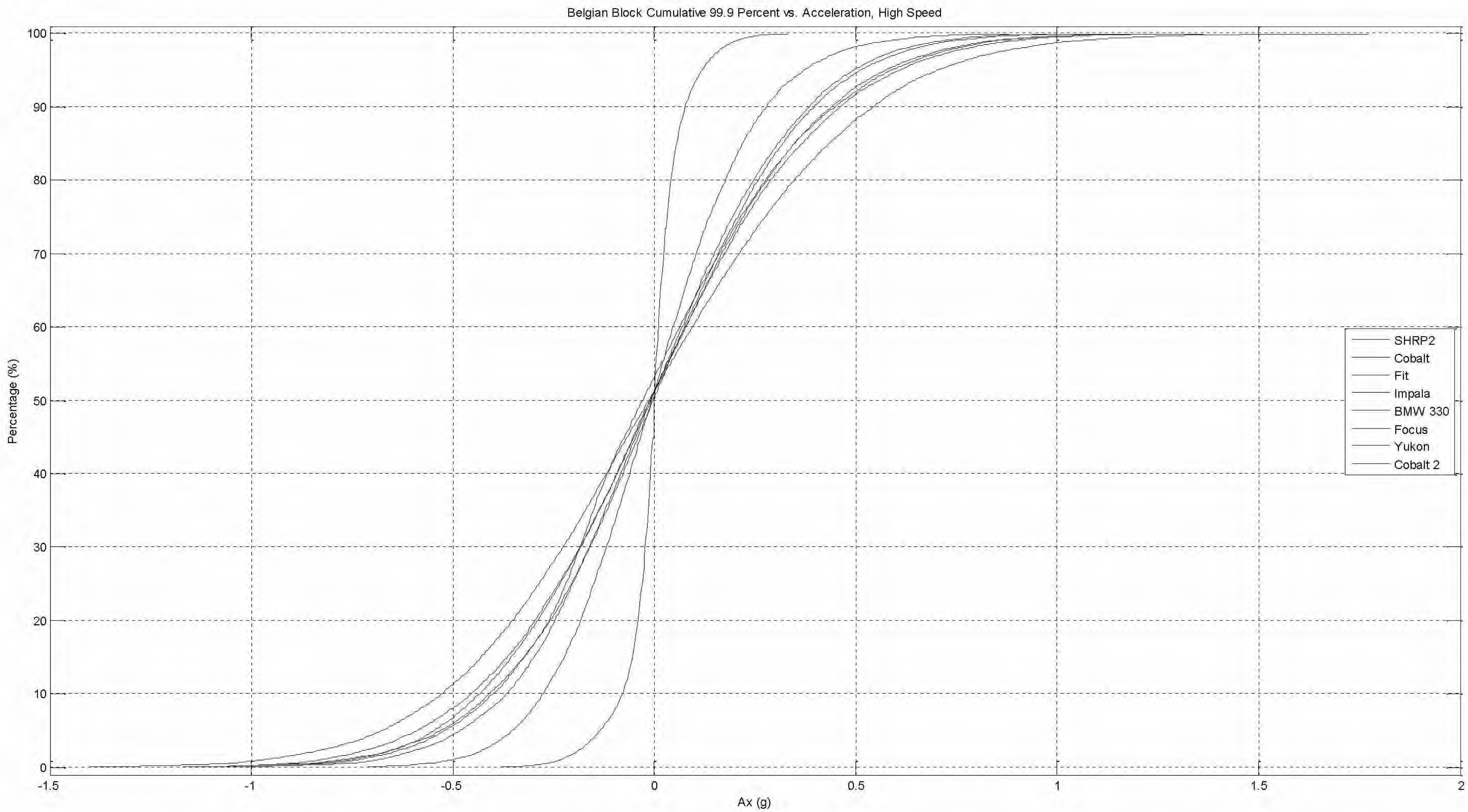
189


Belgian Block Cumulative Percentage vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Az (g)
100
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6

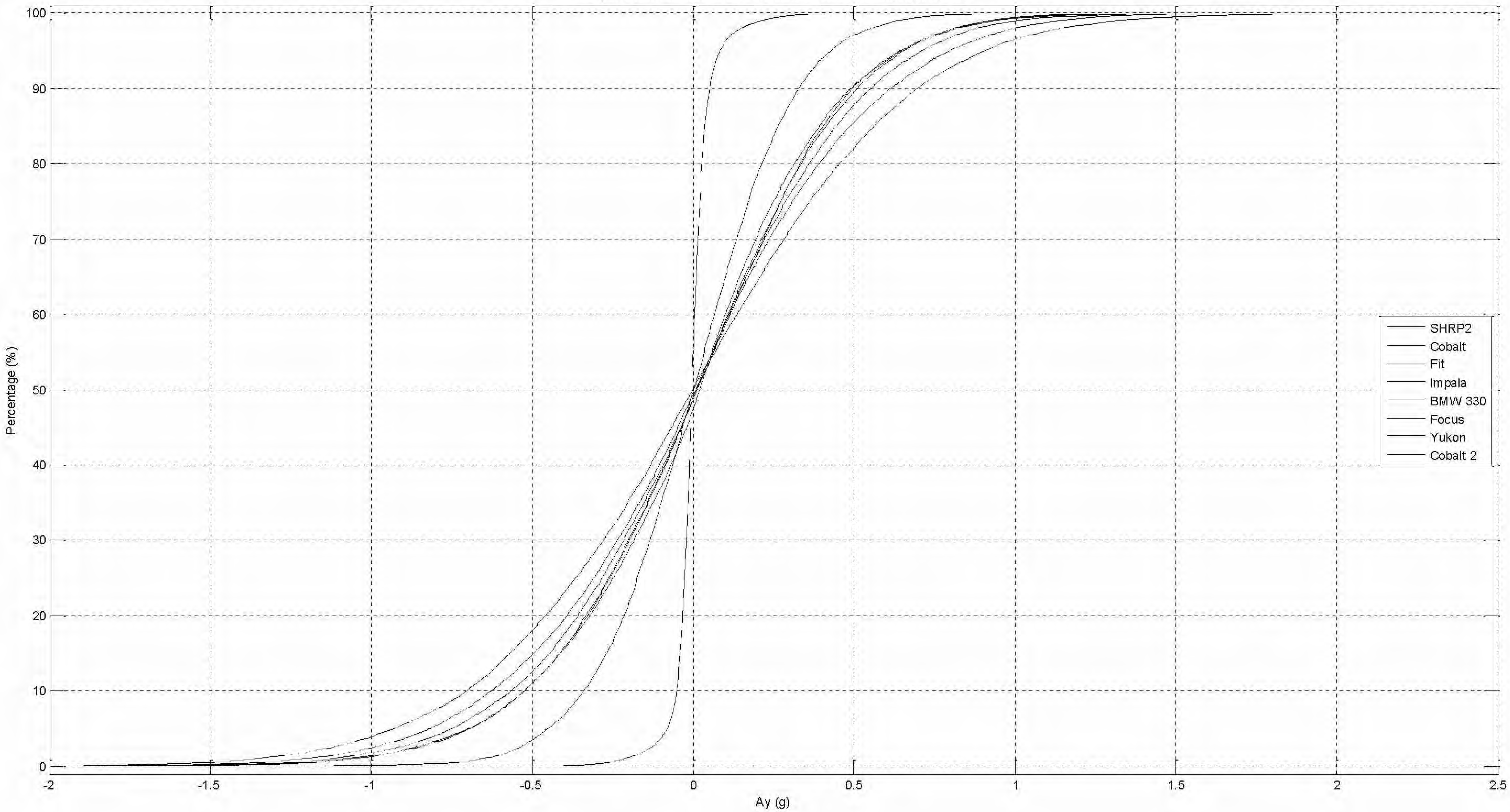
190

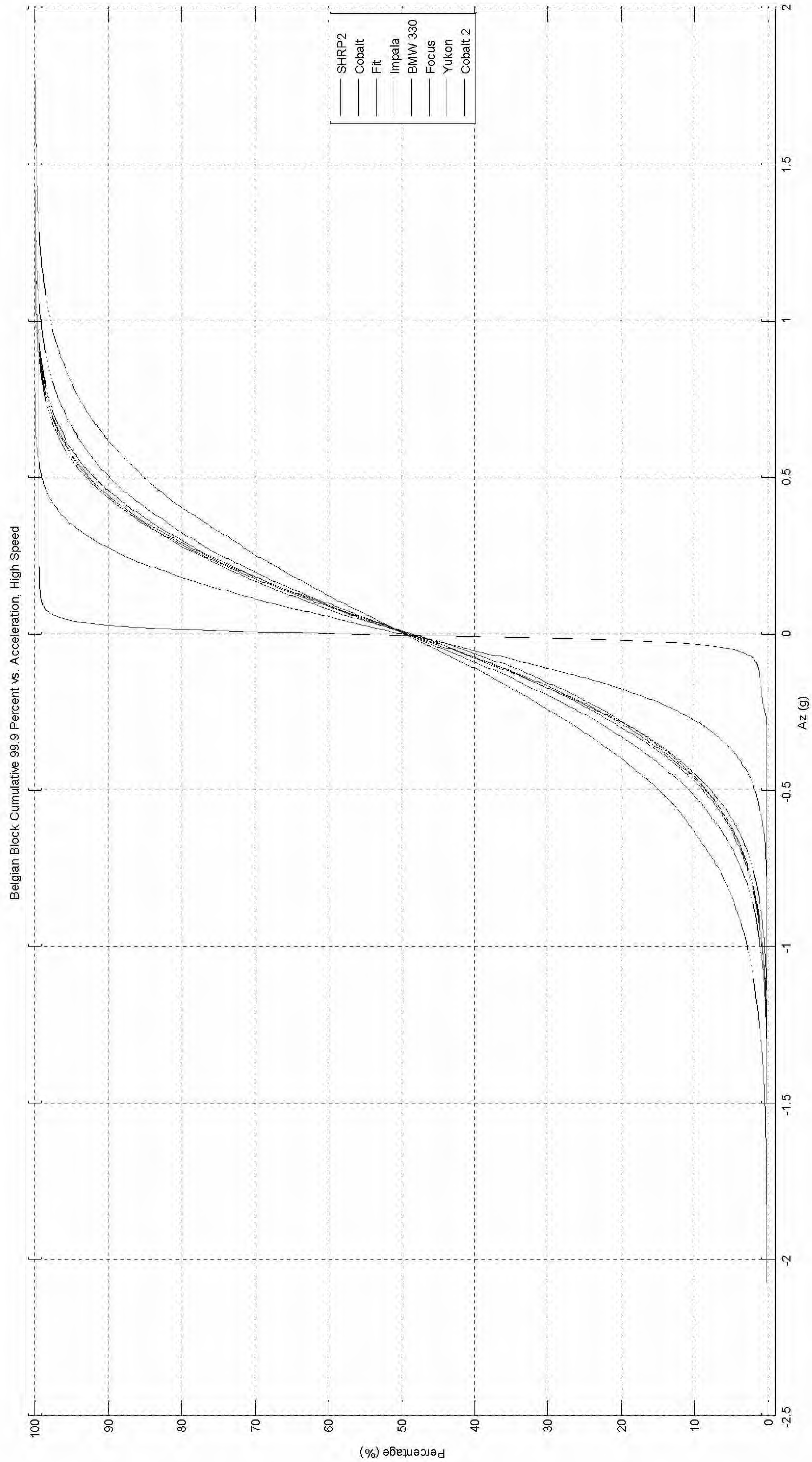
Belgian Block, High- and Low-speed 99.9% Plots

High Speed



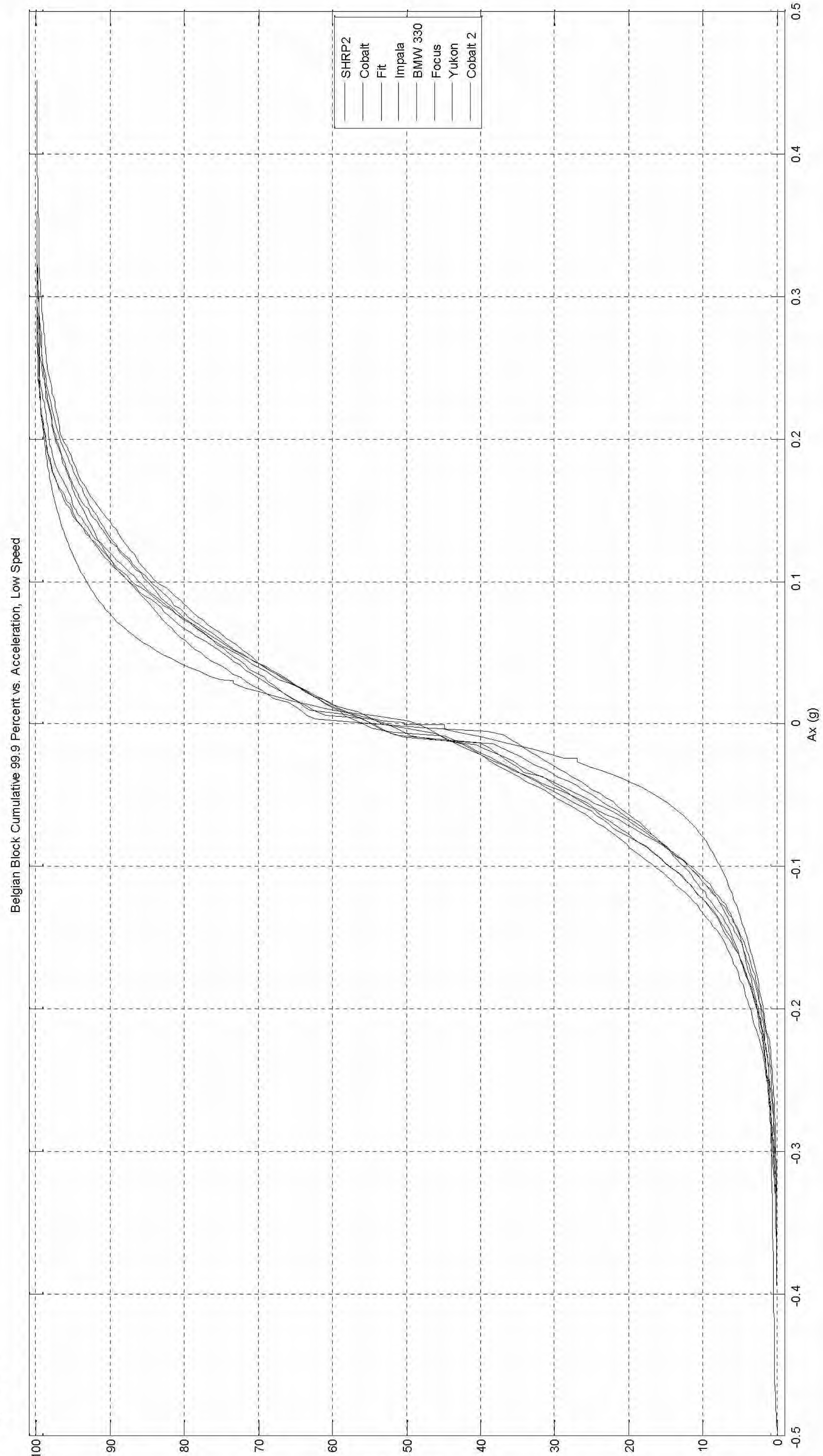
Belgian Block Cumulative 99.9 Percent vs. Acceleration, High Speed




Belgian Block Cumulative 99.9 Percent vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Az (g)
100
90
80
70
60
50
40
30
20
10
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

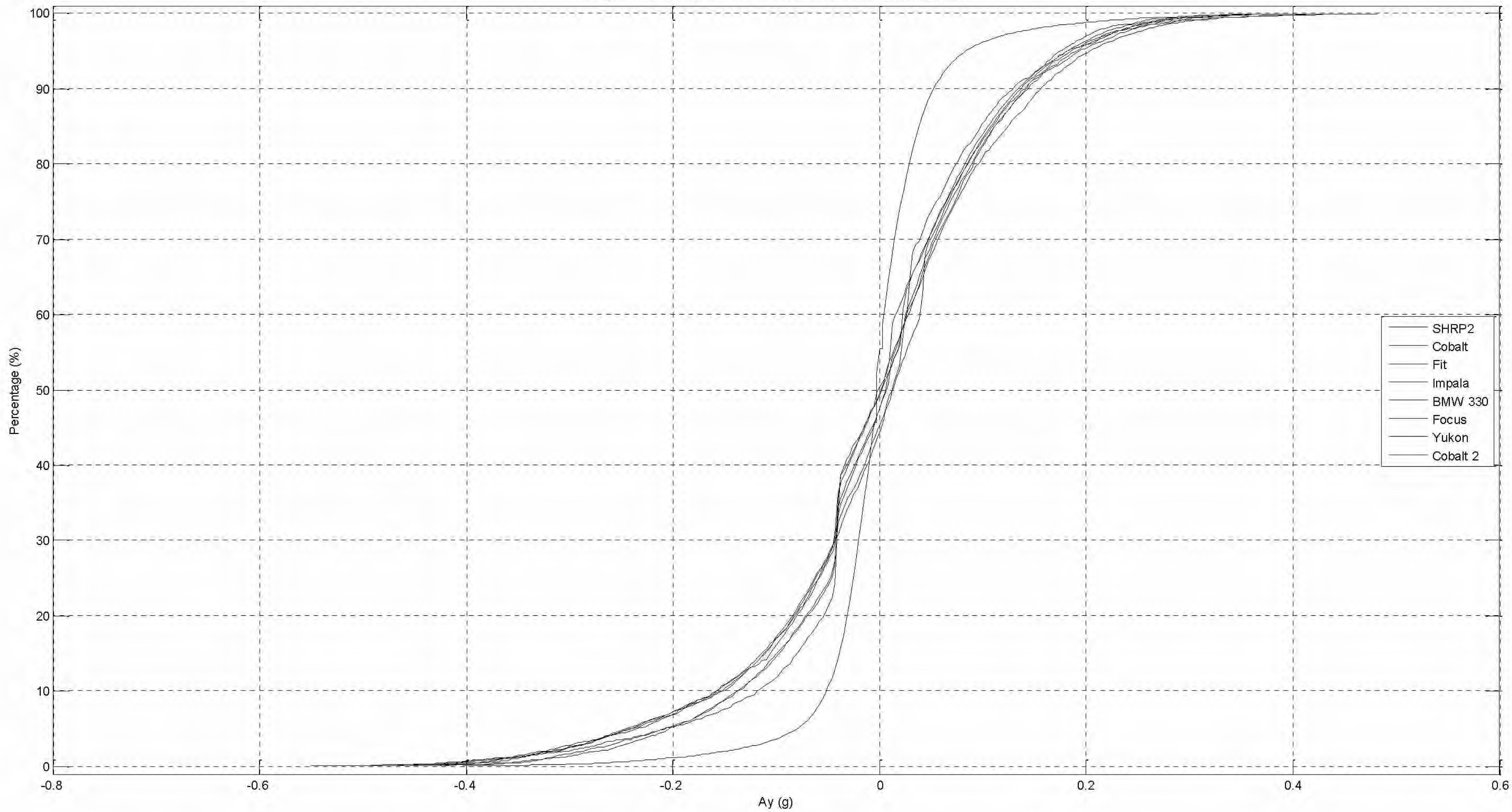
193

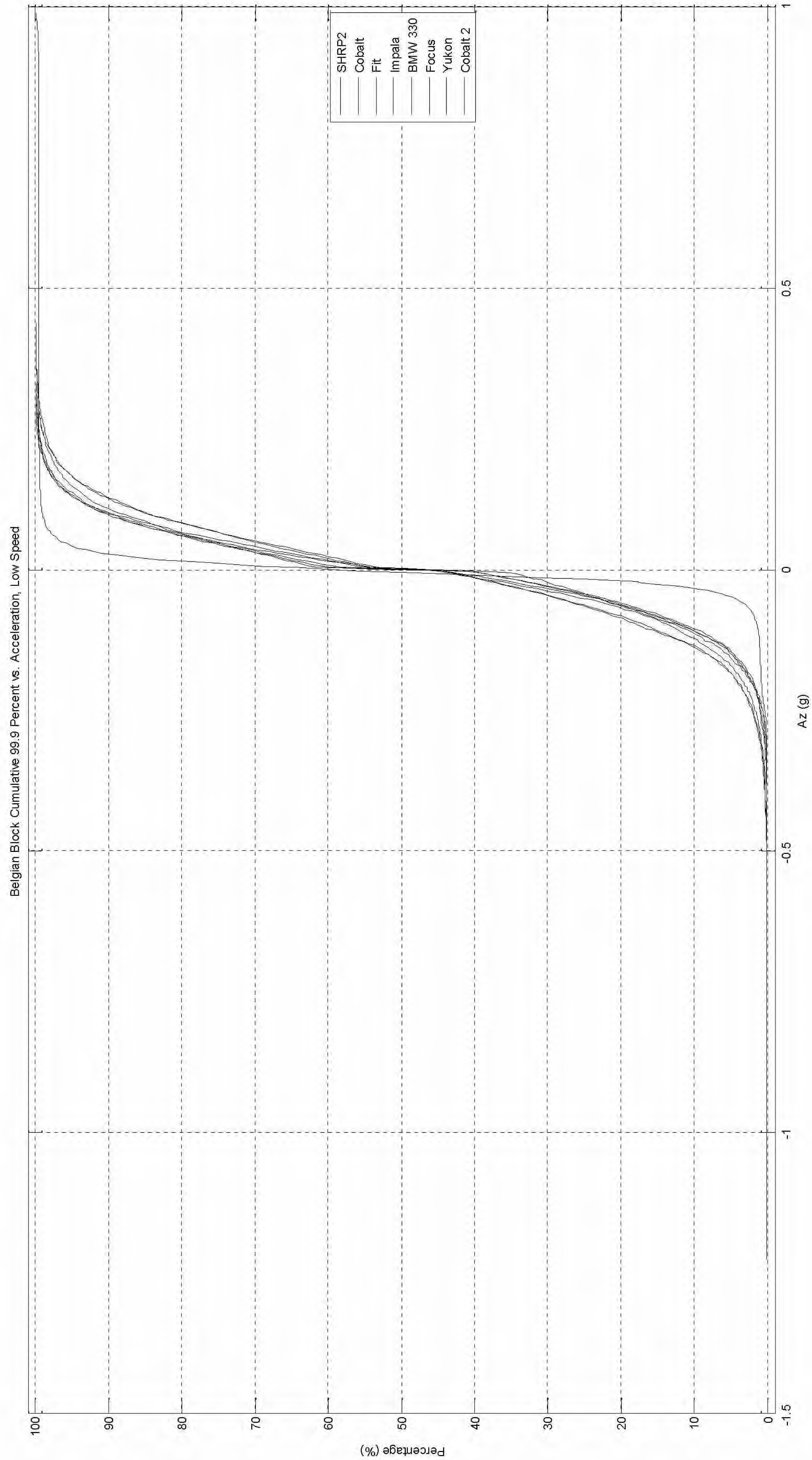
Low Speed



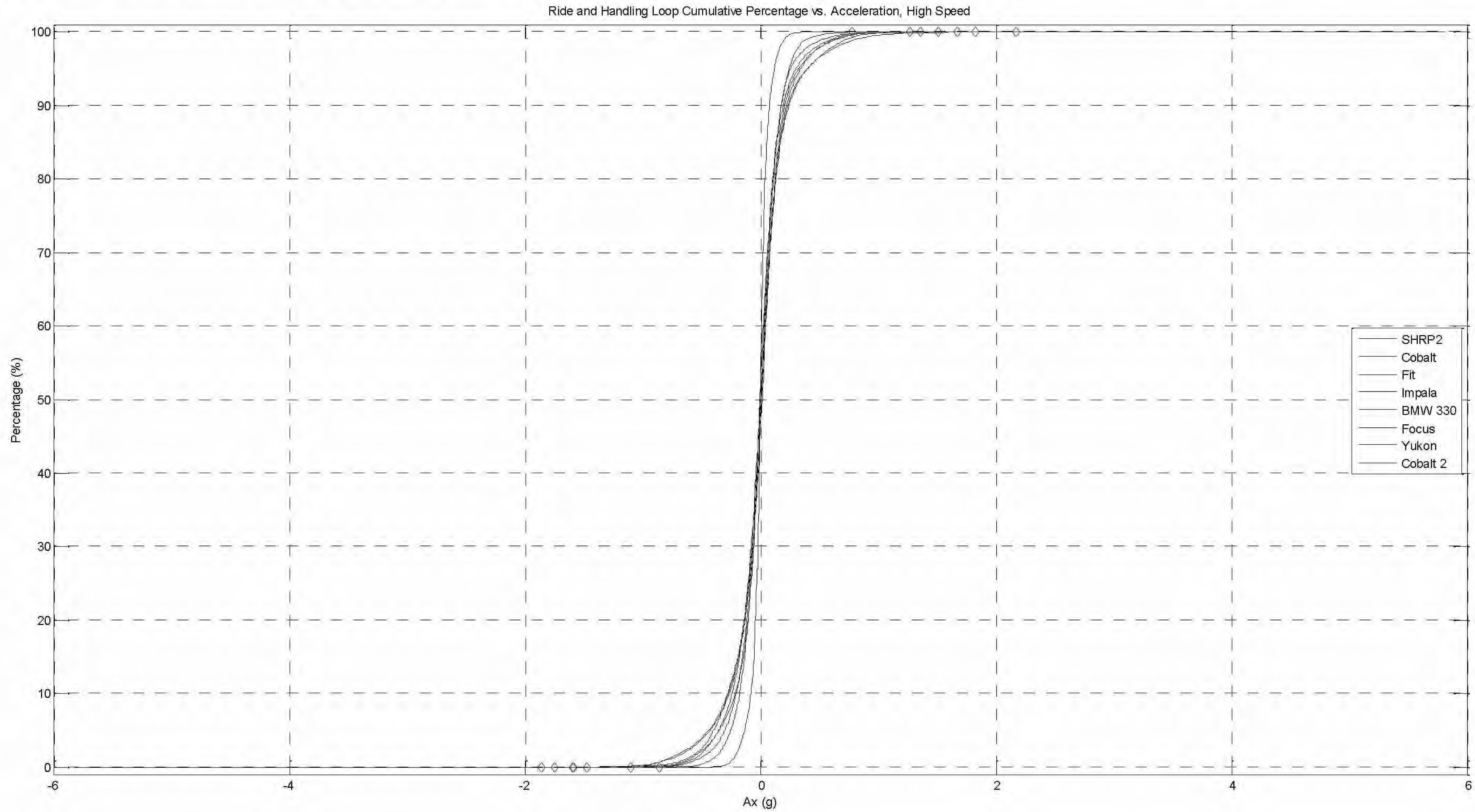
194

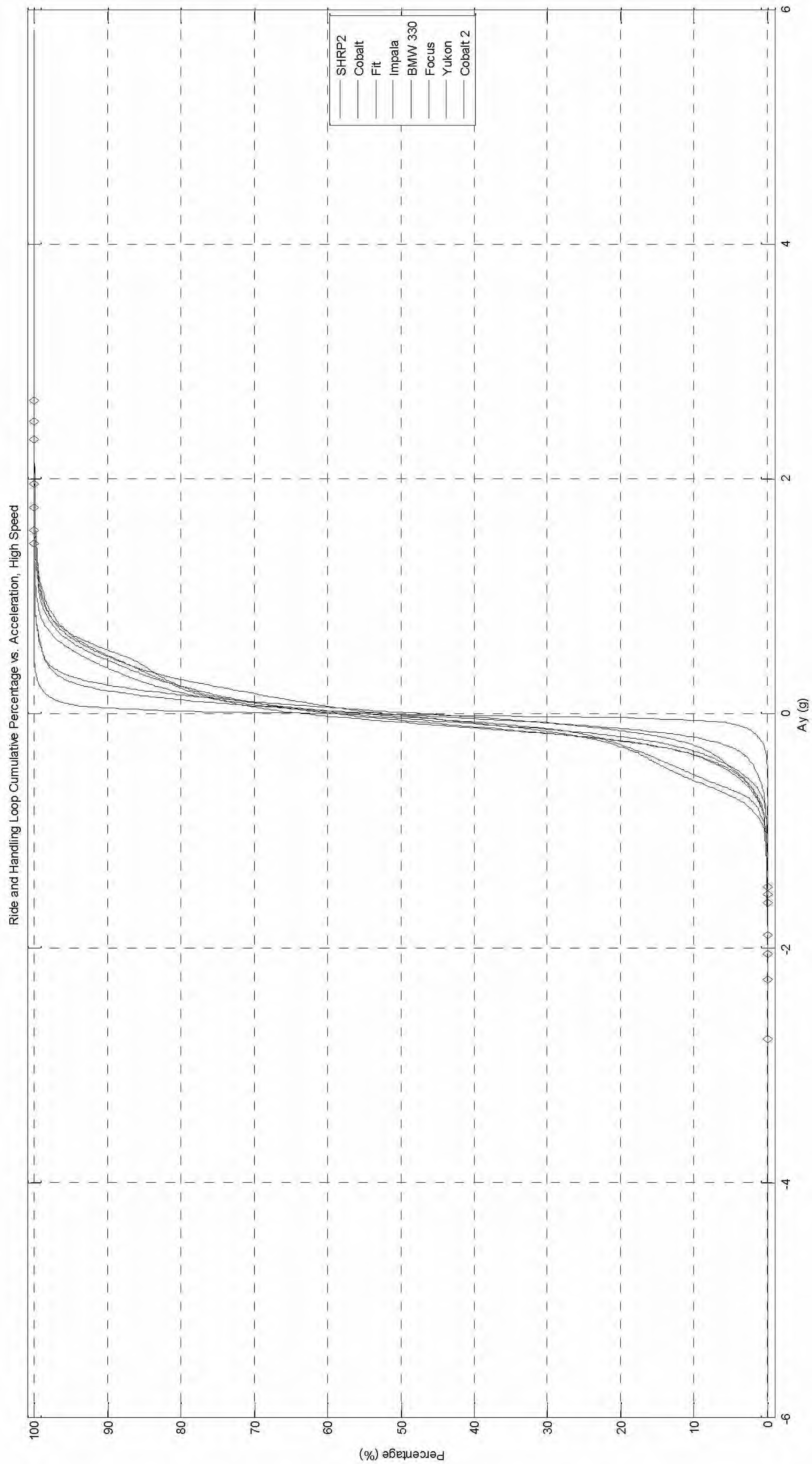
Belgian Block Cumulative 99.9 Percent vs. Acceleration, Low Speed



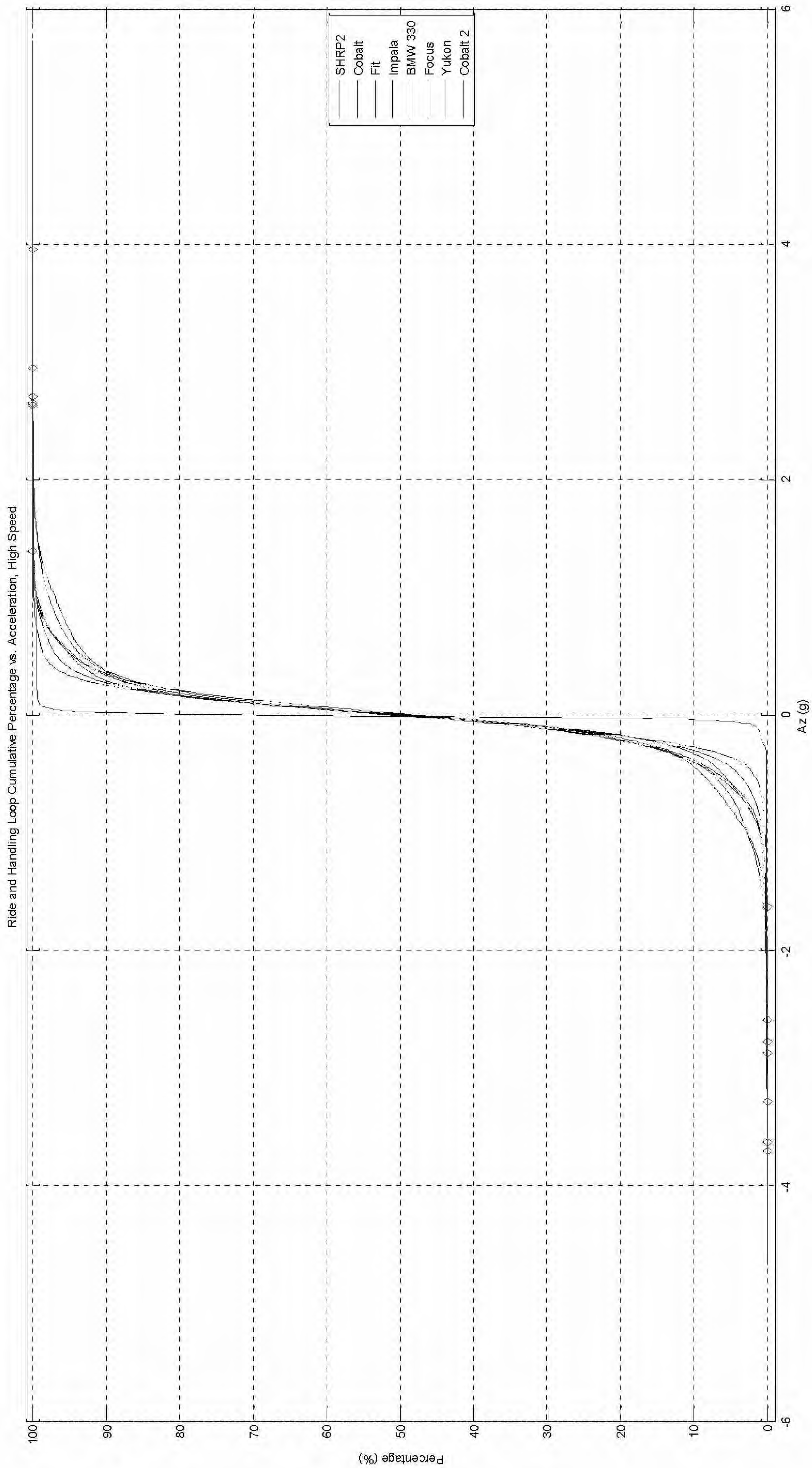

Belgian Block Cumulative 99.9 Percent vs. Acceleration, Low Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
Az (g)

Ride and Handling Loops #1 and #2, 100% Plots



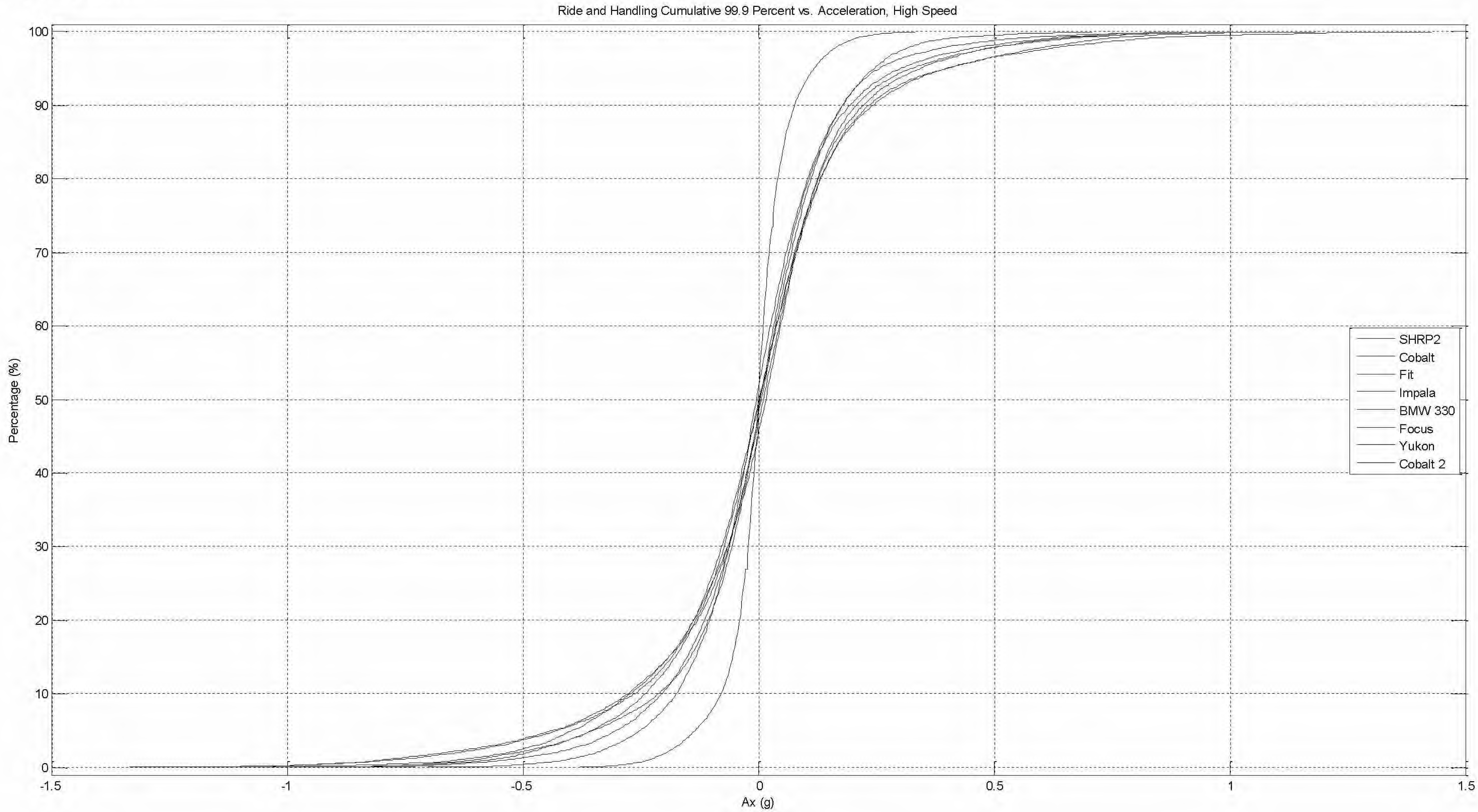

Ride and Handling Loop Cumulative Percentage vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
Ay (g)
-6
-4
-2
0
2
4
6

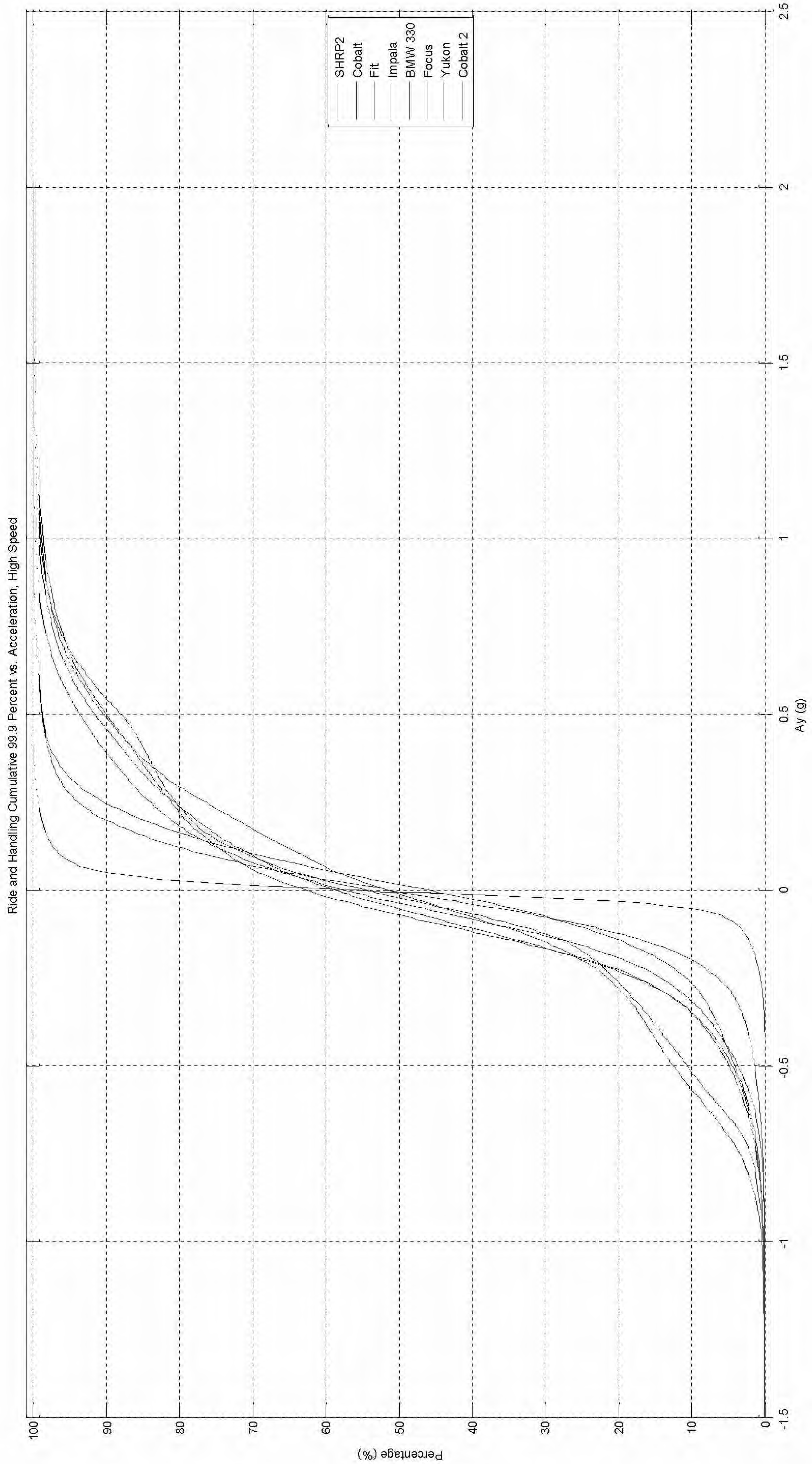
198

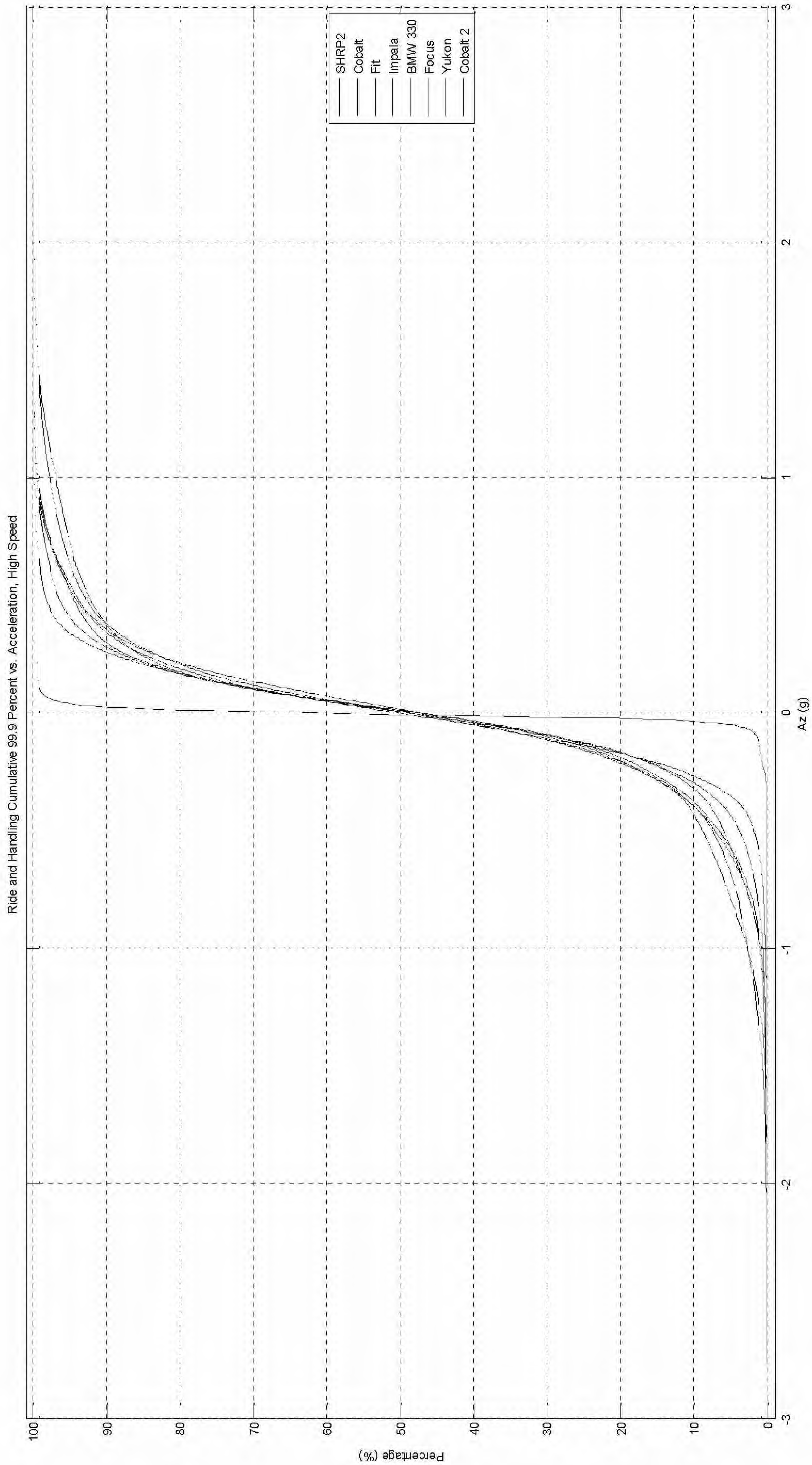

Ride and Handling Loop Cumulative Percentage vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Az (g)
100
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6

Ride and Handling Loops #1 and #2, High- and Low-speed 99.9% Plots

High Speed

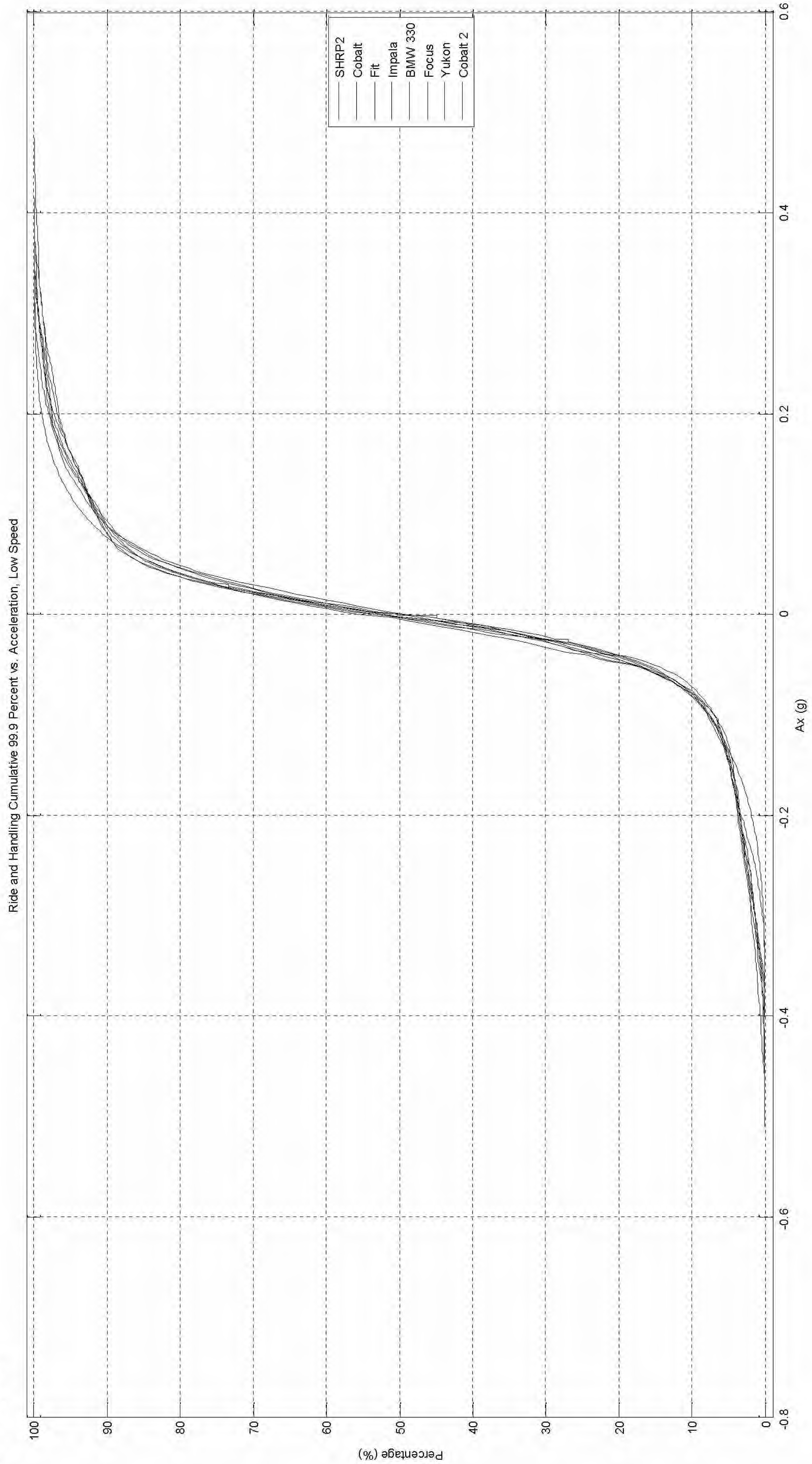


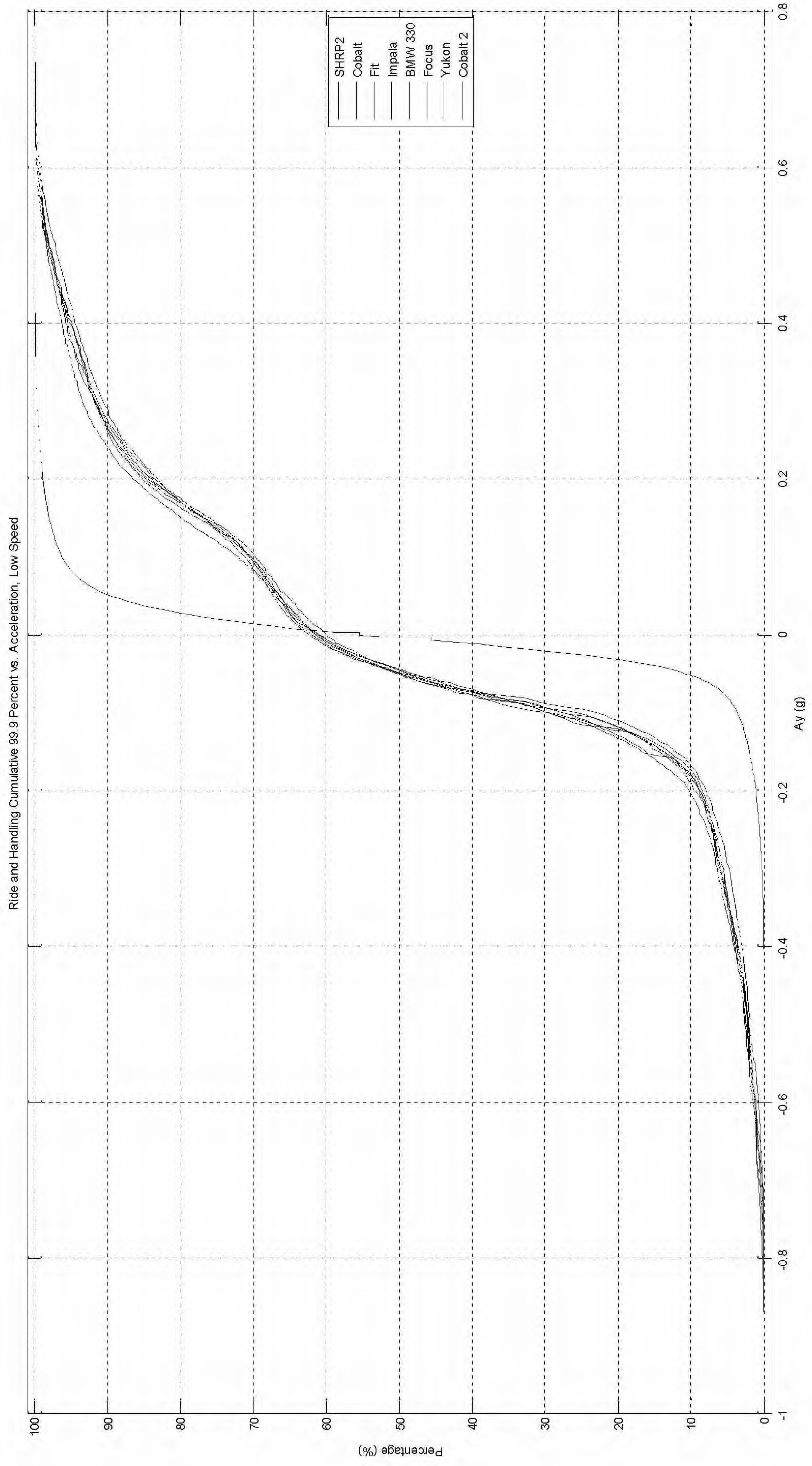

Ride and Handling Cumulative 99.9 Percent vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Ay (g)
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

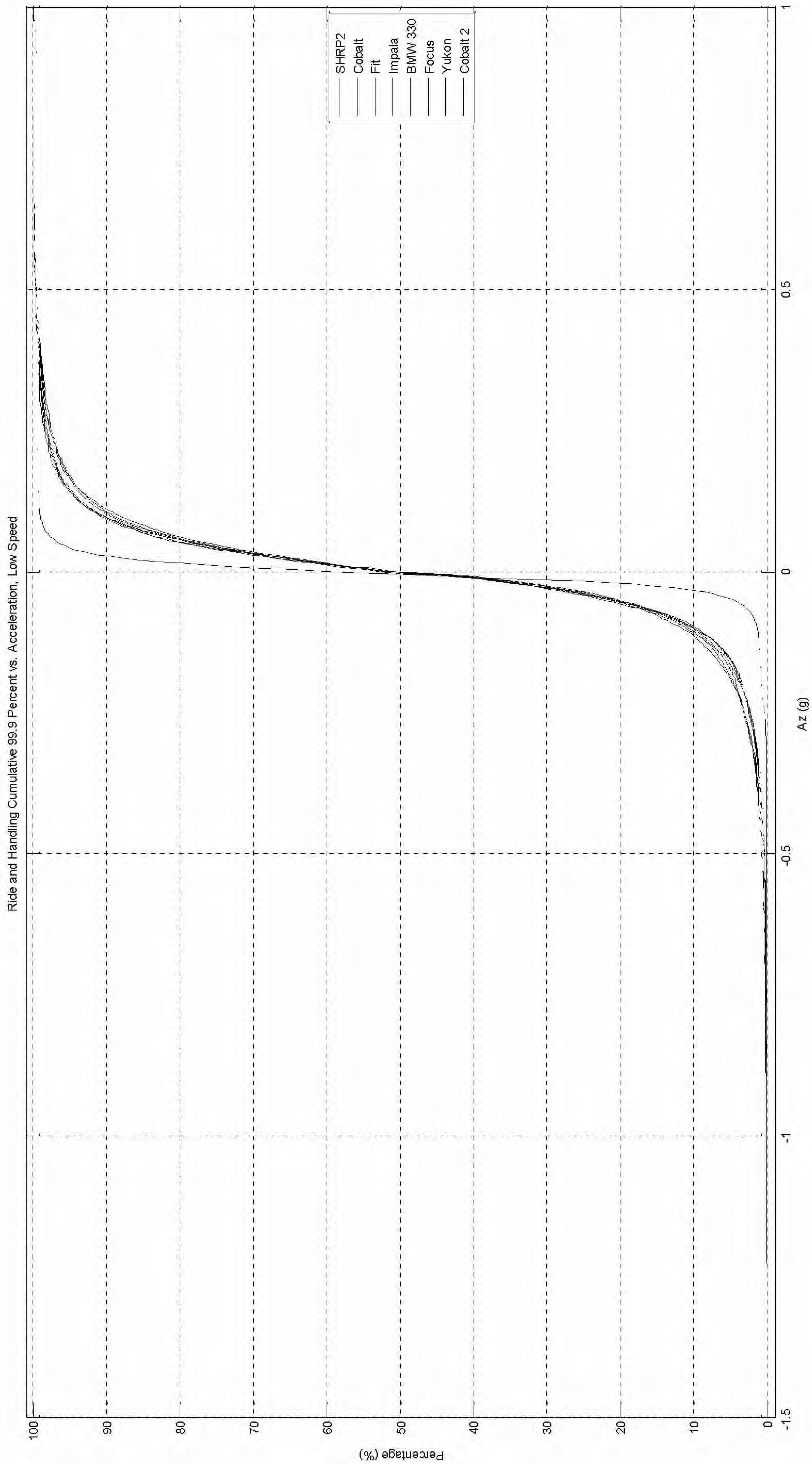

Ride and Handling Cumulative 99.9 Percent vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
0
10
20
30
40
50
60
70
80
90
100
Az (g)
-3
-2
-1
0
1
2
3

202

Low Speed

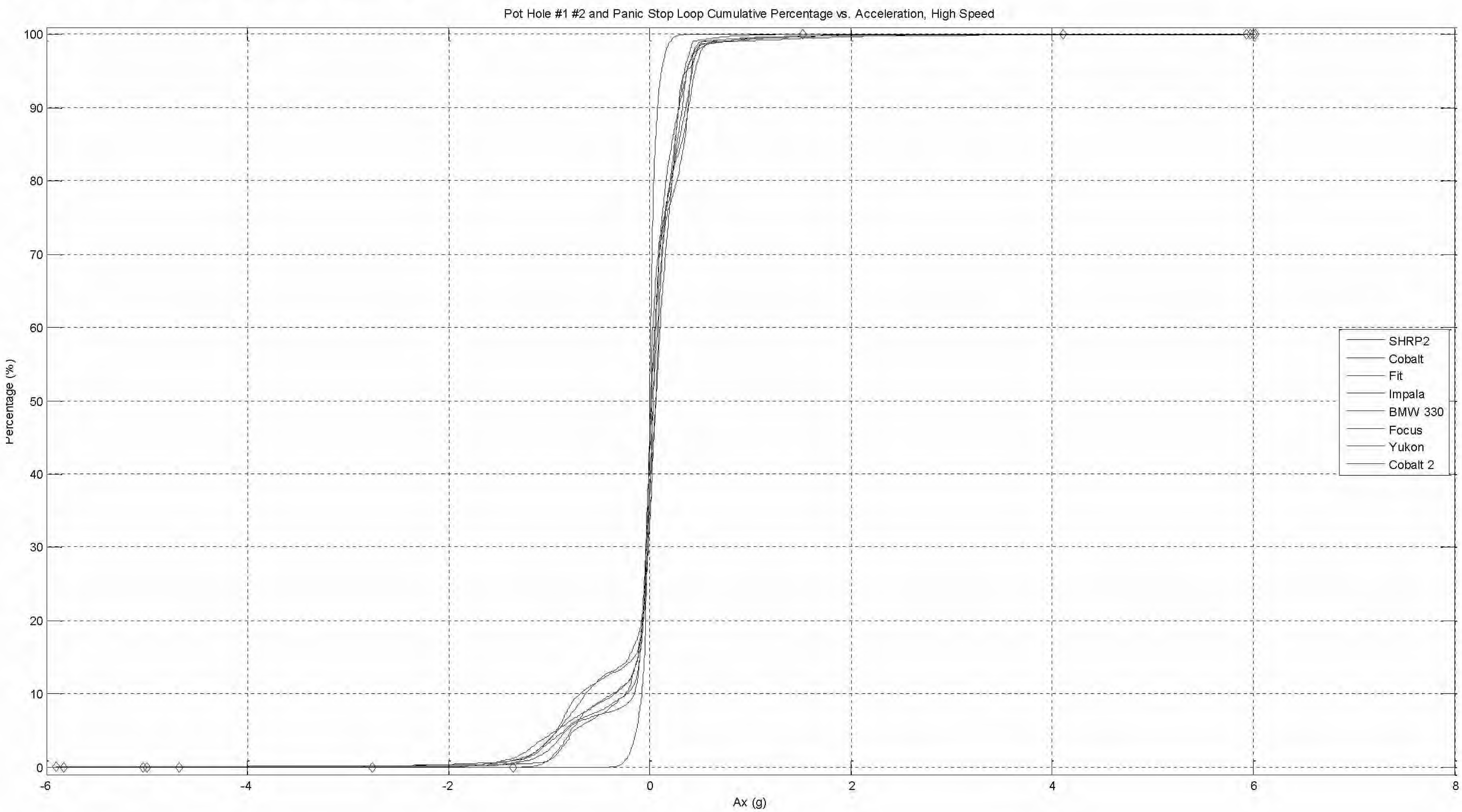

Ride and Handling Cumulative 99.9 Percent vs. Acceleration, Low Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
Ax (g)
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

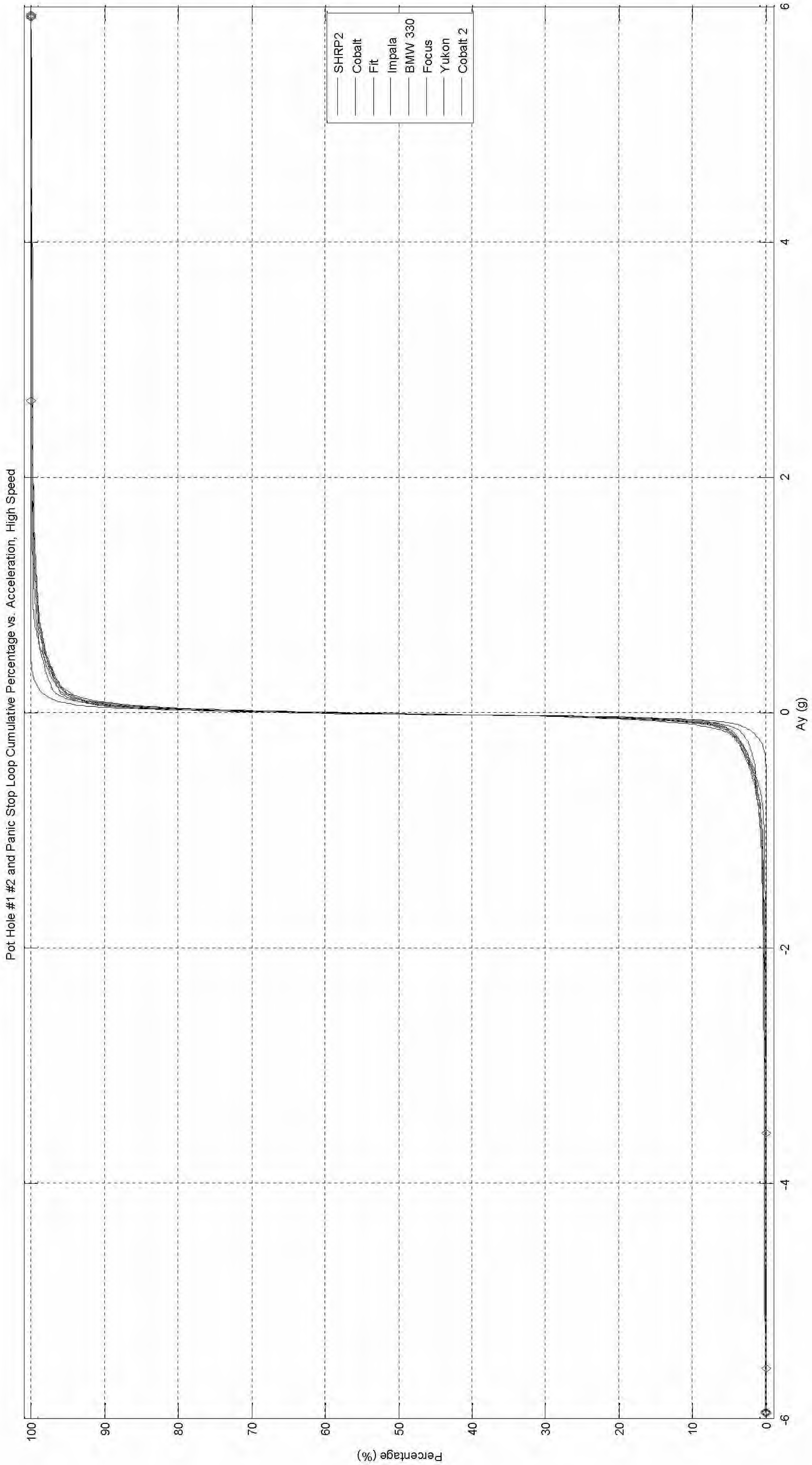

Ride and Handling Cumulative 99.9 Percent vs. Acceleration, Low Speed
Percentage (%)
Ay (g)
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
100
90
80
70
60
50
40
30
20
10
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8


Ride and Handling Cumulative 99.9 Percent vs. Acceleration, Low Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Az (g)
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1

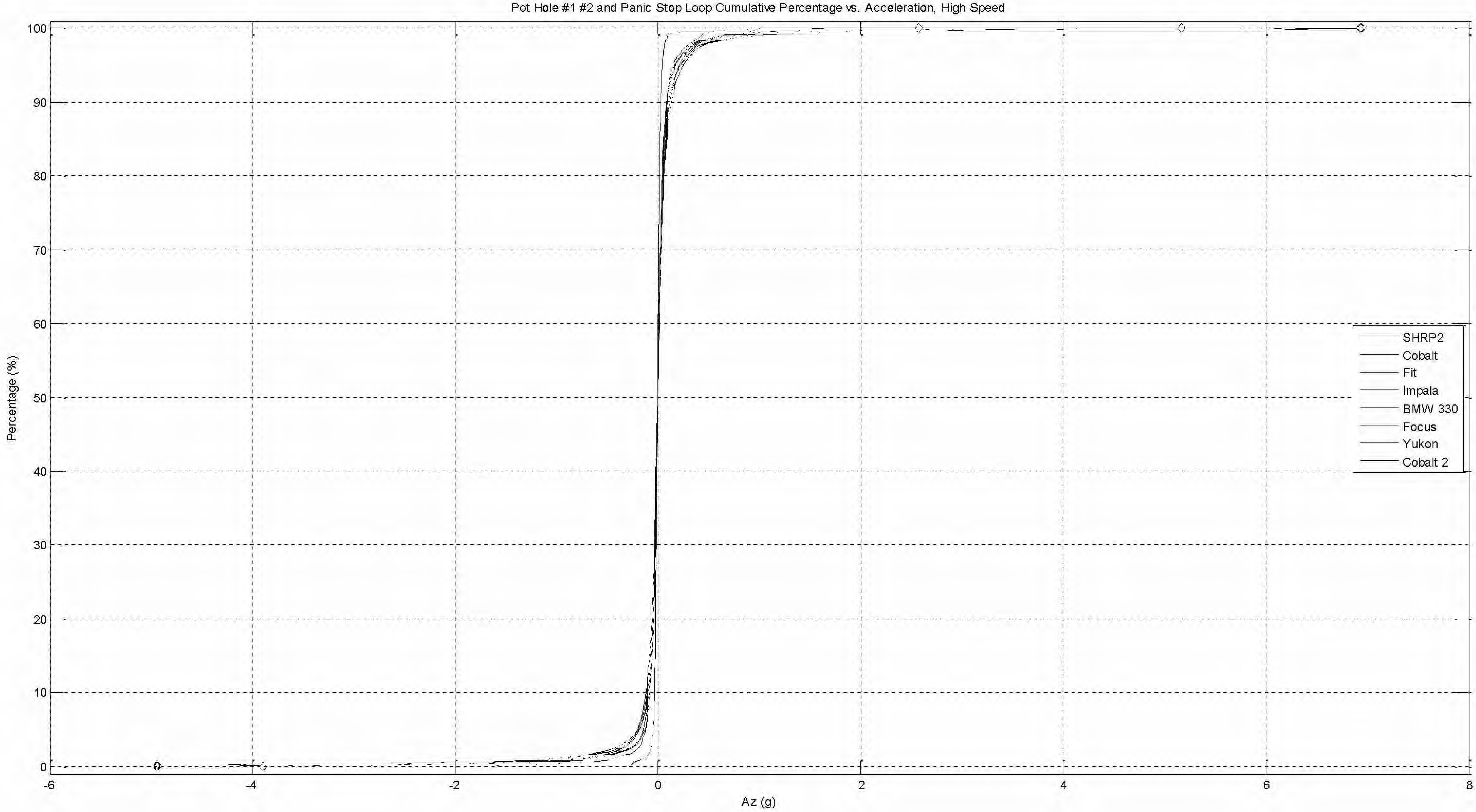
205

Potholes #1 and #2 and Panic Stop, High-speed 100% Plots



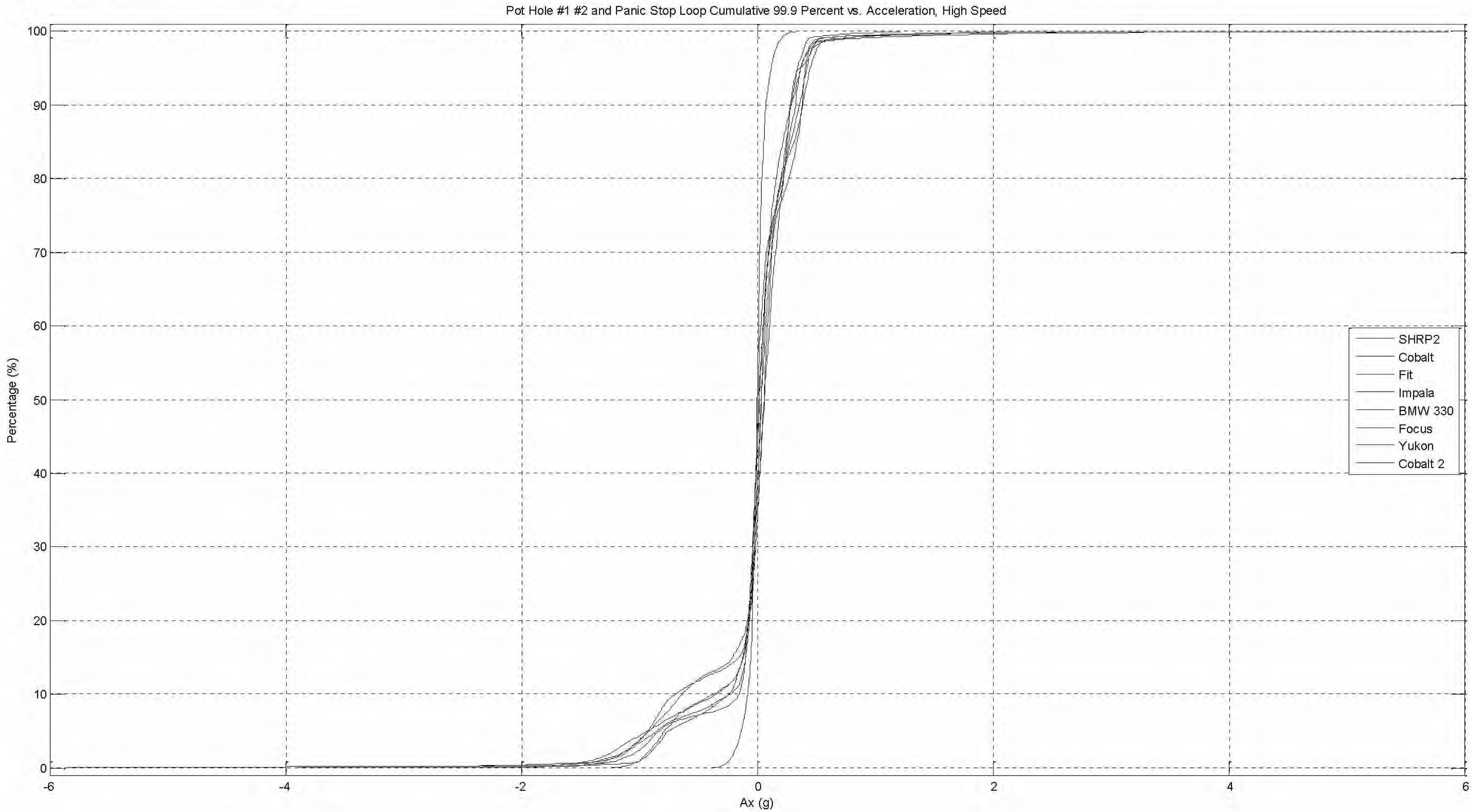

Pot Hole #1 #2 and Panic Stop Loop Cumulative Percentage vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Ay (g)
100
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6

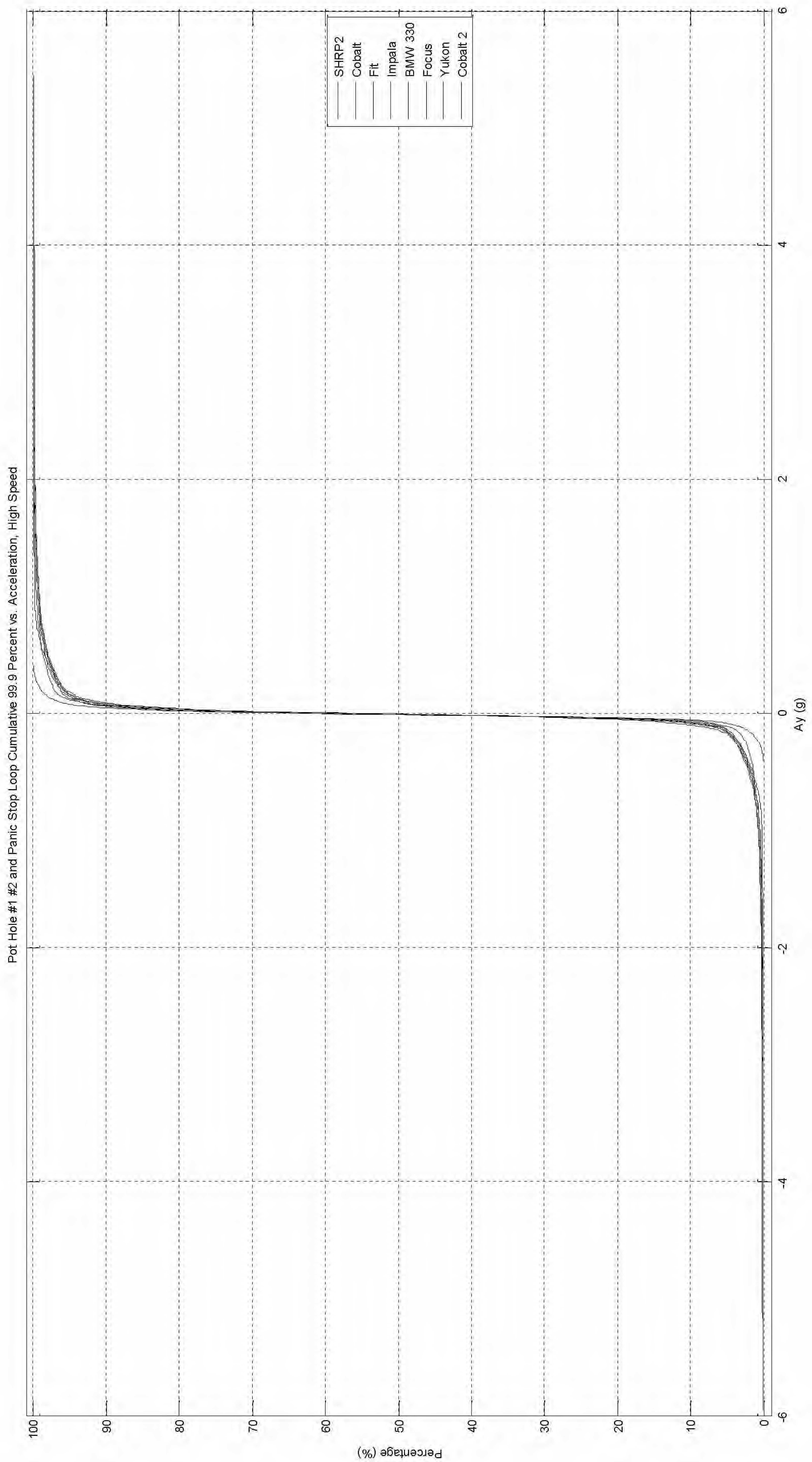
Pot Hole #1 #2 and Panic Stop Loop Cumulative Percentage vs. Acceleration, High Speed



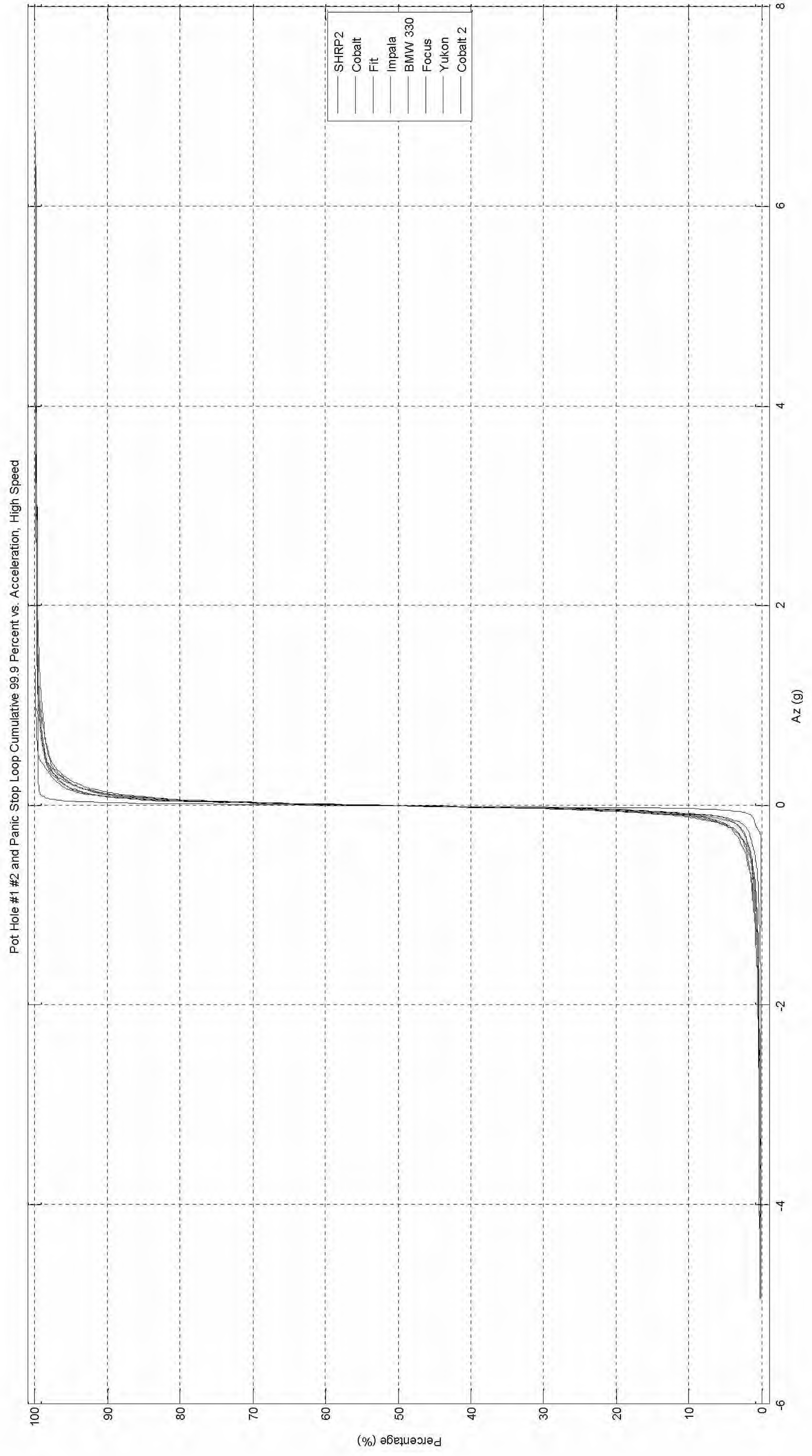
Potholes #1 and #2 and Panic Stop, High- and Low-speed 99.9% Plots

High Speed



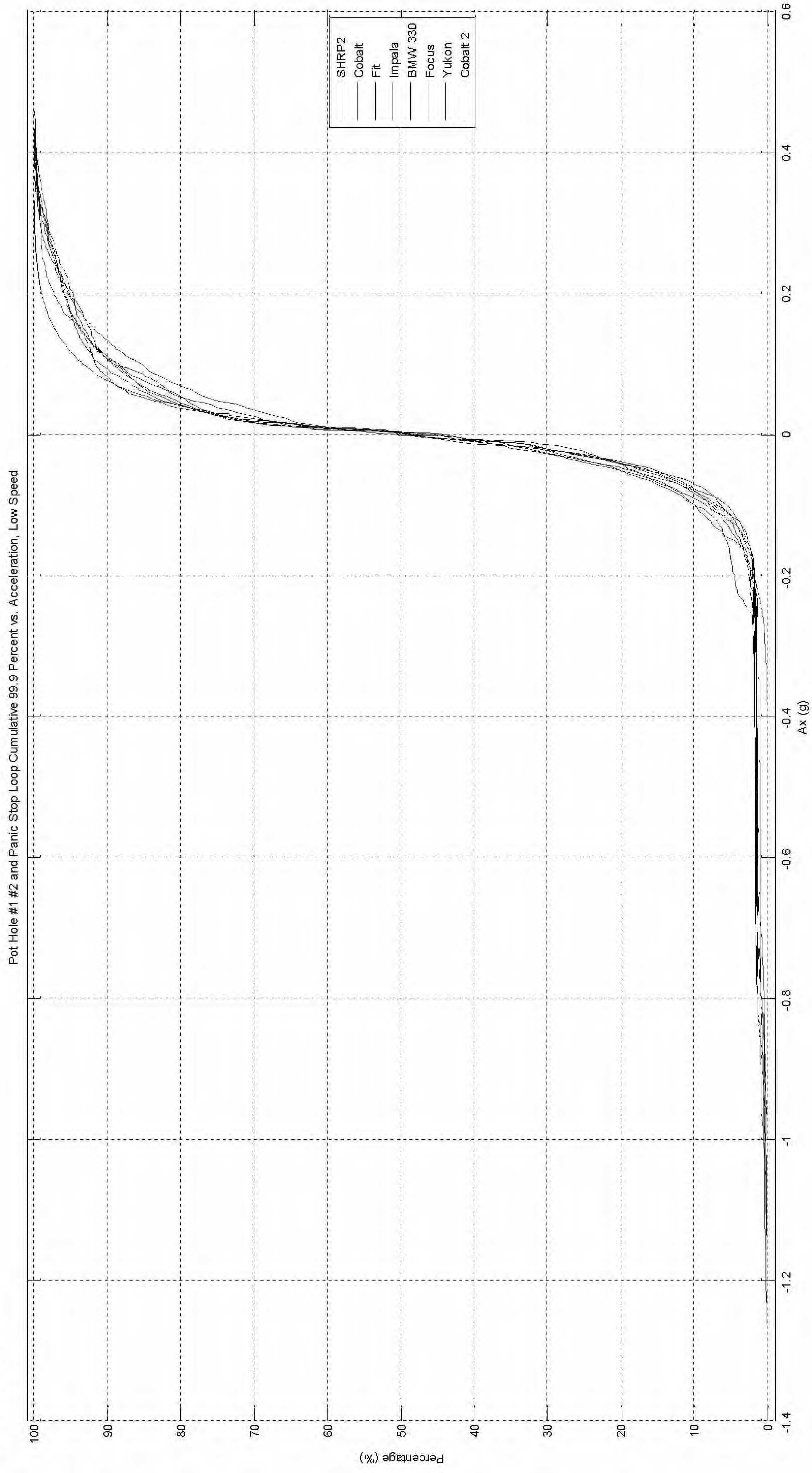

Pot Hole #1 #2 and Panic Stop Loop Cumulative 99.9 Percent vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
Ay (g)

210


Pot Hole #1 #2 and Panic Stop Loop Cumulative 99.9 Percent vs. Acceleration, High Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
Az (g)
100
90
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
8

211

Low Speed



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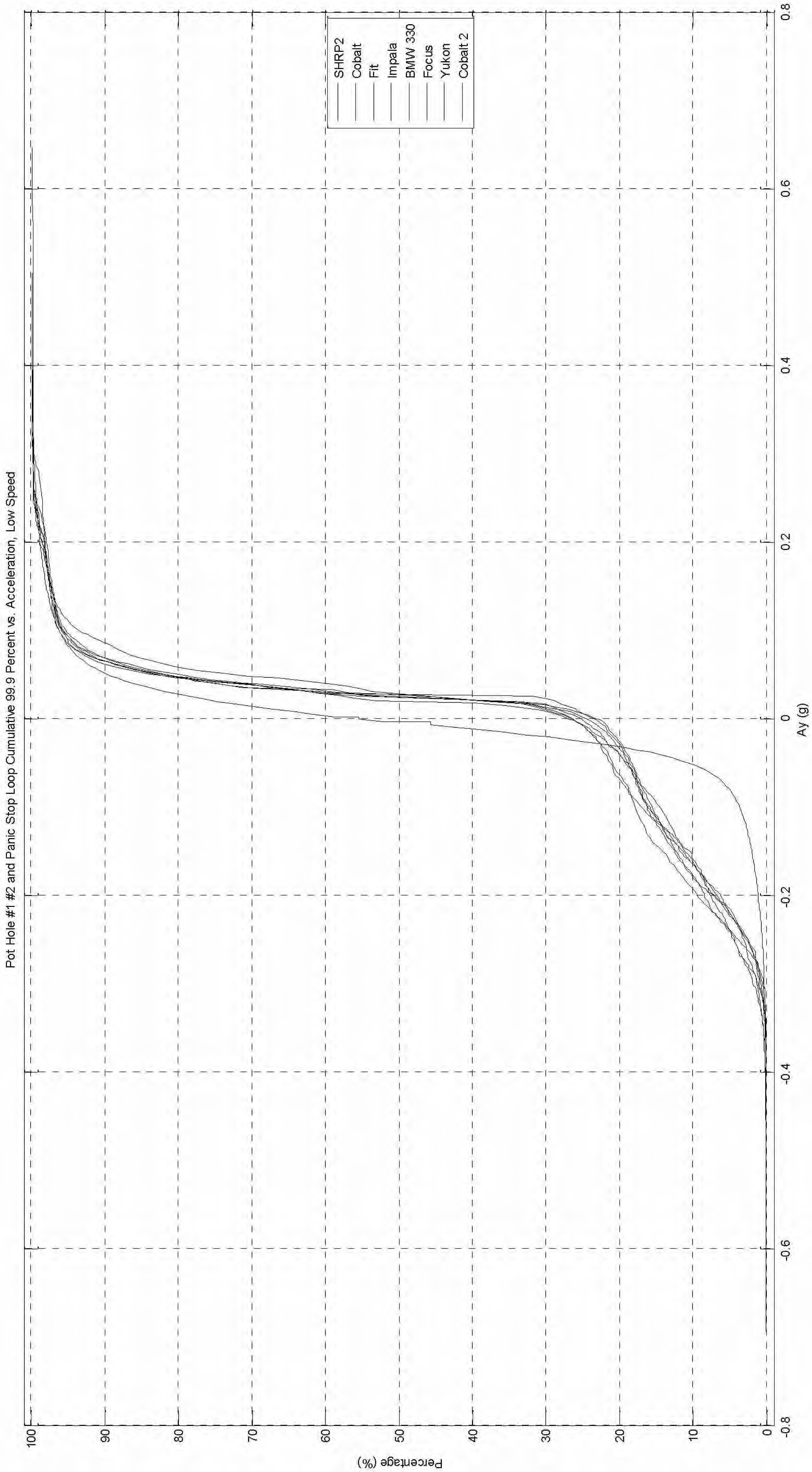
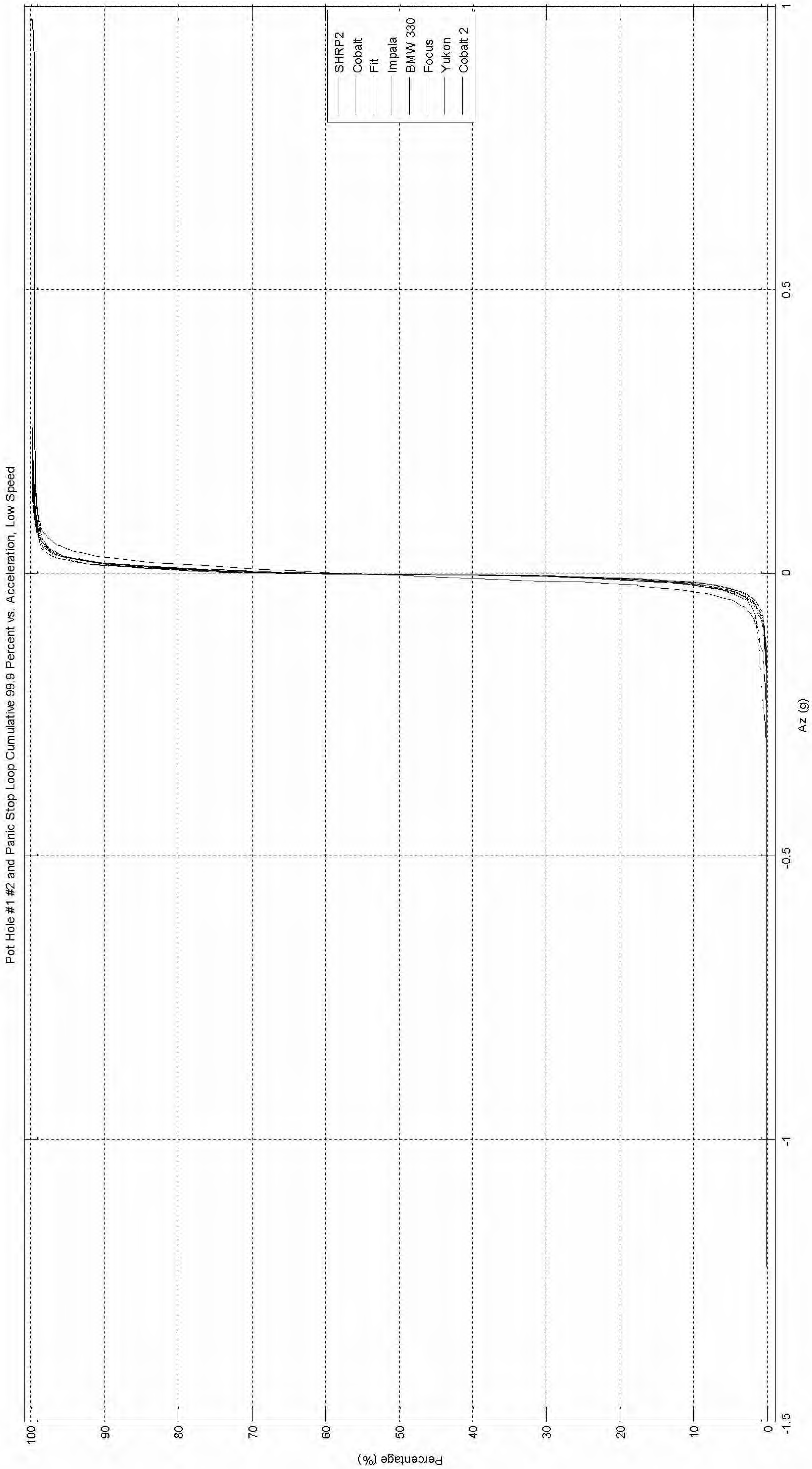

Pot Hole #1 #2 and Panic Stop Loop Cumulative 99.9 Percent vs. Acceleration, Low Speed
Percentage (%)
Ay (g)
100
90
80
70
60
50
40
30
20
10
0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2


Pot Hole #1 #2 and Panic Stop Loop Cumulative 99.9 Percent vs. Acceleration, Low Speed
SHRP2
Cobalt
Fit
Impala
BMW 330
Focus
Yukon
Cobalt 2
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
-1.5
-1
-0.5
0
0.5
1
Az (g)